Flash-level relationship of FORTE VHF signals and strokes detected by NLDN

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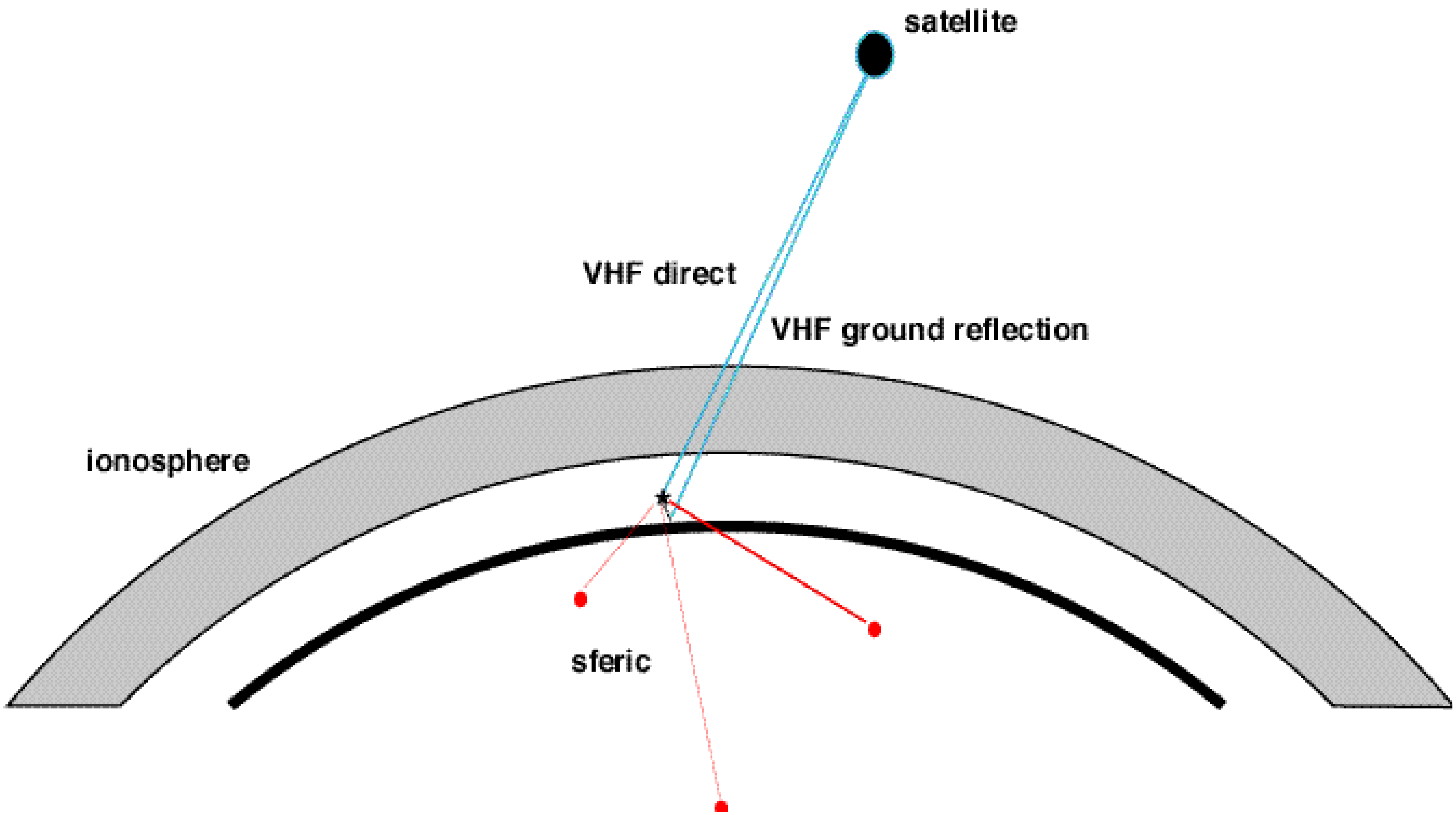
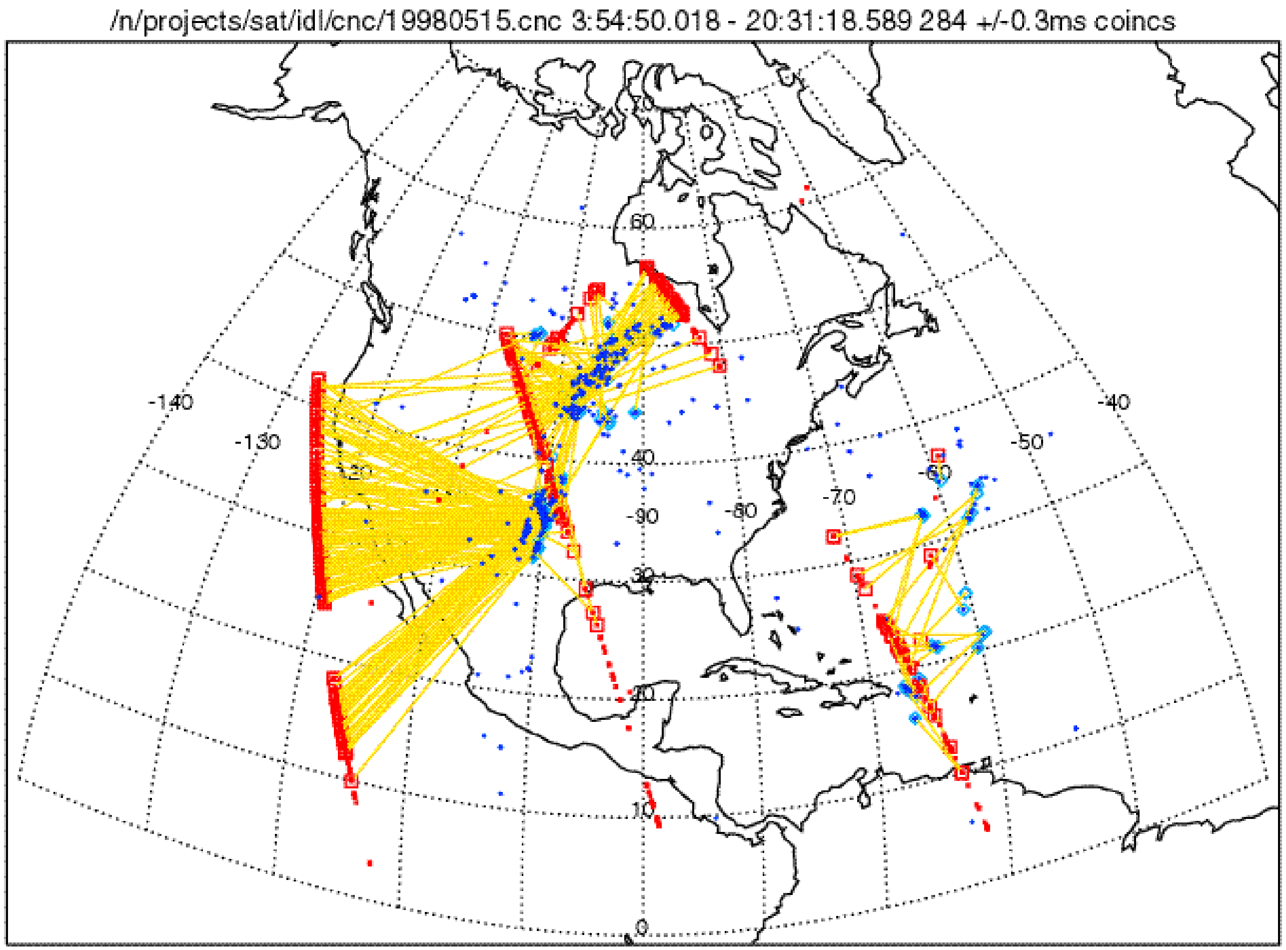
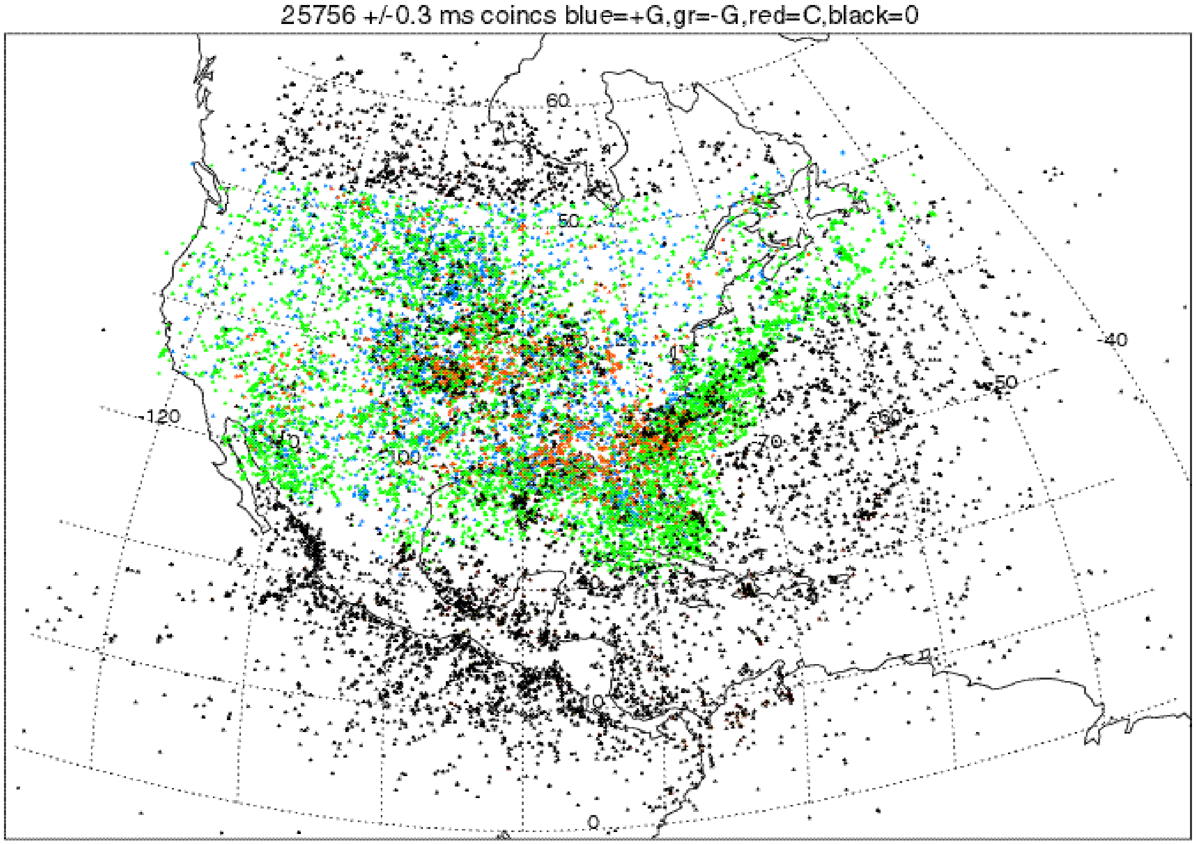
The FORTE satellite's rf receivers record VHF (30-300 MHz) emissions associated with lightning. The National Lightning Detection Network (NLDN) detects and characterizes lightning strokes by their lower-frequency "sferic" signal, at some tens of kHz. We have used the NLDN/FORTE joint observations of Apr-Sept 1998 and May-Oct 1999 to amass about 25,000 coincident events, in which both sensor systems saw the same event to within a coincidence of ±300 μs referred to the source location given by NLDN. The goal is to characterize the signals which a satellite constellation could use to monitor/characterize lightning activity.

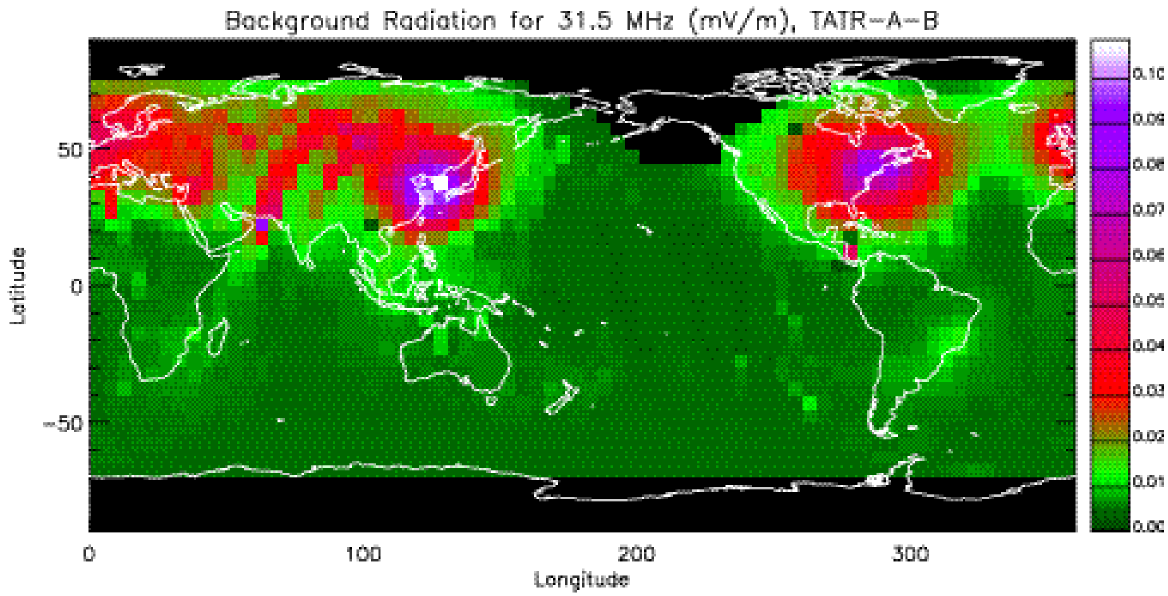


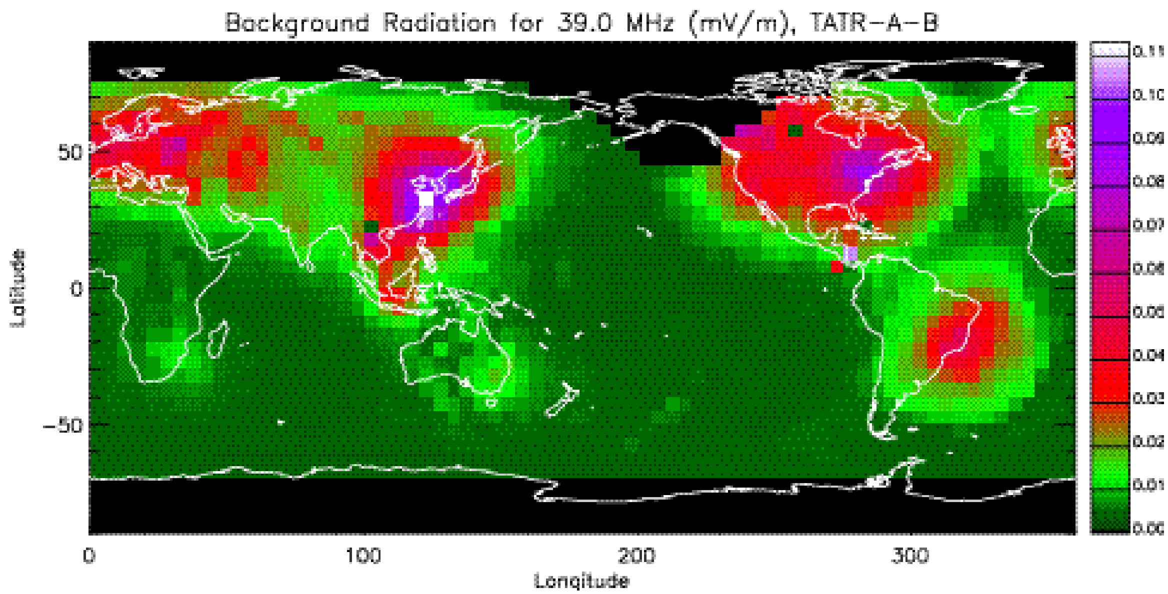
This shows a UT day's FORTE coincidences with NLDN. The subsatellite point is shown in red, the NLDN points in blue. Yellow lines connect coincident FORTE and NLDN events. Descending passes are NW to SE, while ascending are SW to NE. Also in blue are NLDN events within ±200 ms of coincident events.



Locations of all FORTE-coincident NLDN strokes. Green=negative CG, blue=positive CG, red=IC, and black=long-range stroke detections for which classification and vertical current are not determinable.

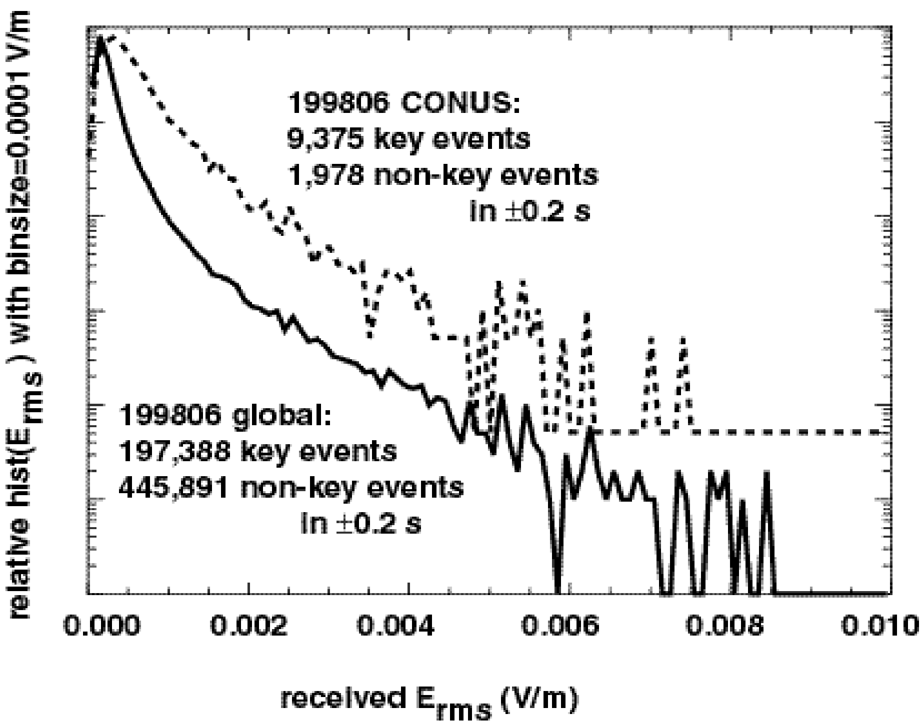


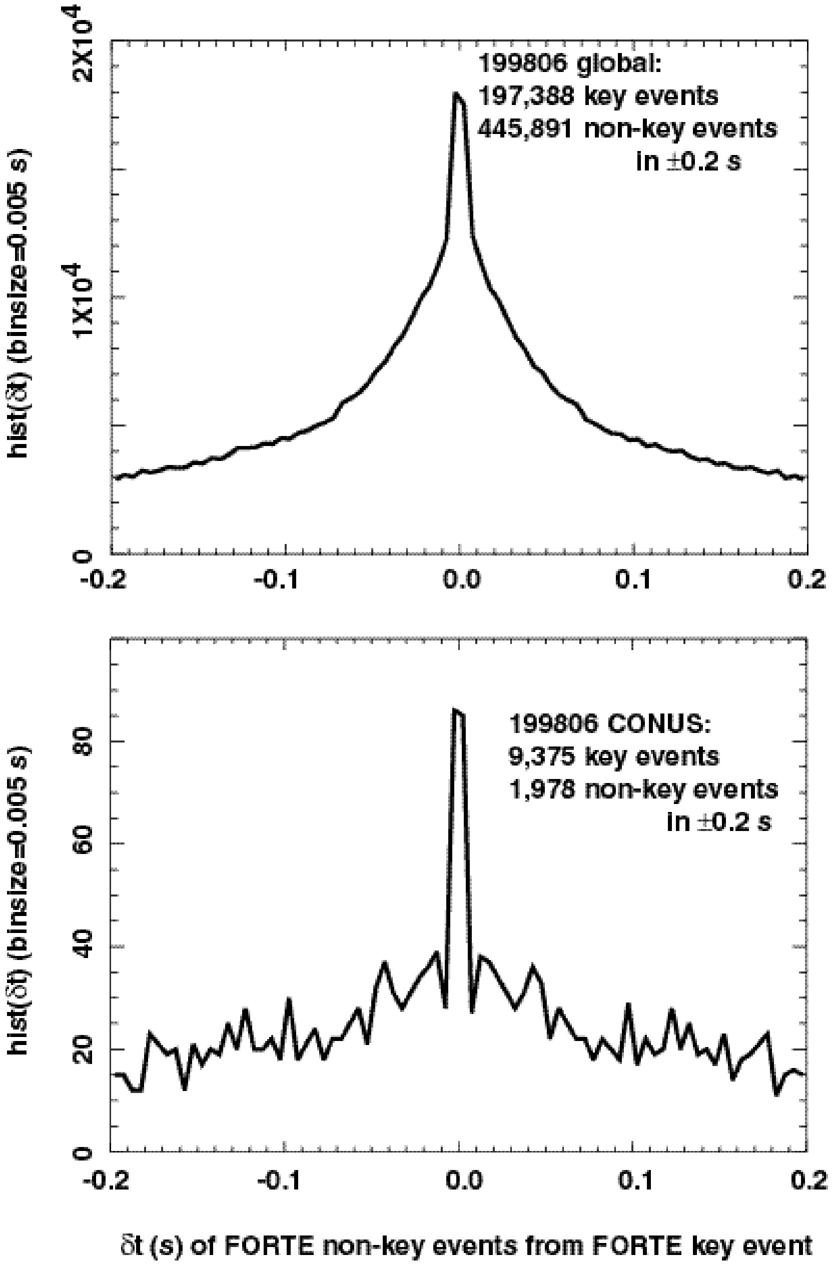




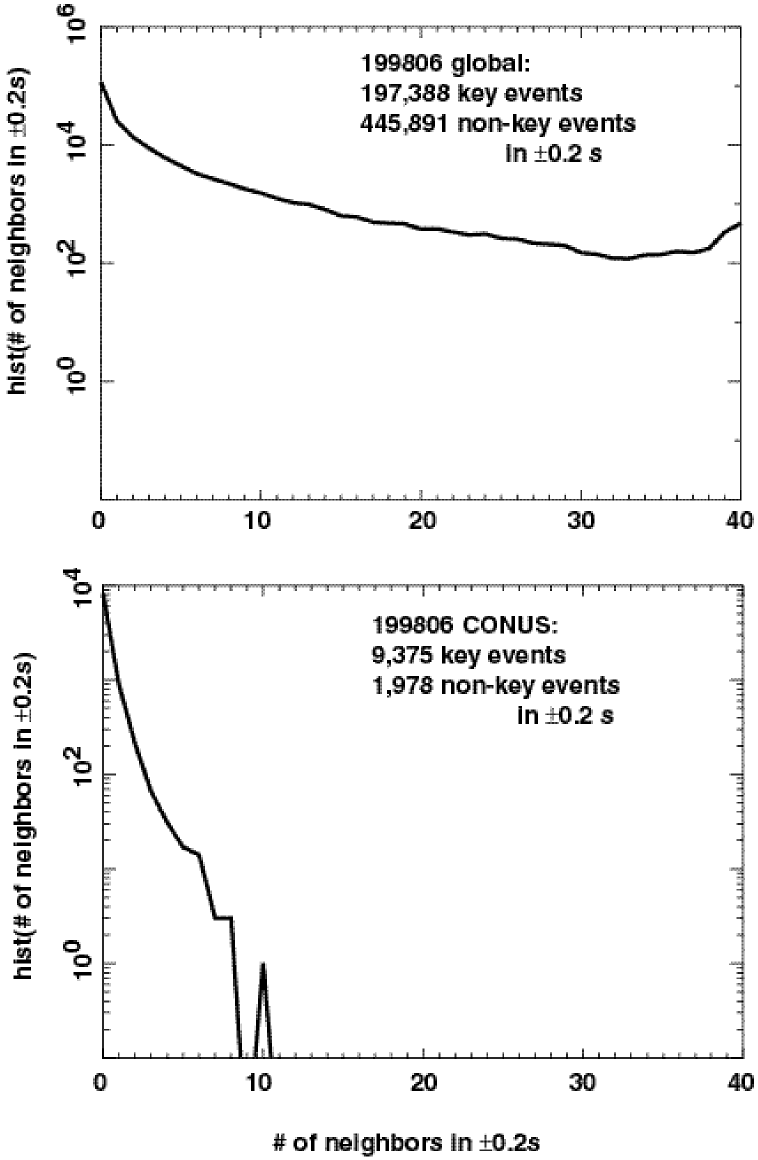
•Global distribution of rms noise electric field at FORTE orbit, in two 1-MHz bands typical of low band (26-48 MHz) [courtesy of T.J. Fitzgerald]. Evident is the higher noise over CONUS,which has the effect of biasing upward the trigger thresholds (which are noise-riding), relative to other areas such as Indonesia and equatorial Africa. This higher effective threshold causes fewer flashes to be detected over the CONUS than over quieter areas. Moreover, within those flashes detected, fewer VHF events per flash are detected

The peak rms electric field in recorded FORTE VHF signals also shows higher values over the CONUS than globally. This is associated with the higher noise levels over the CONUS and hence higher actual trigger thresholds. Below is shown the distribution of peak rms electric field in the recorded signals.



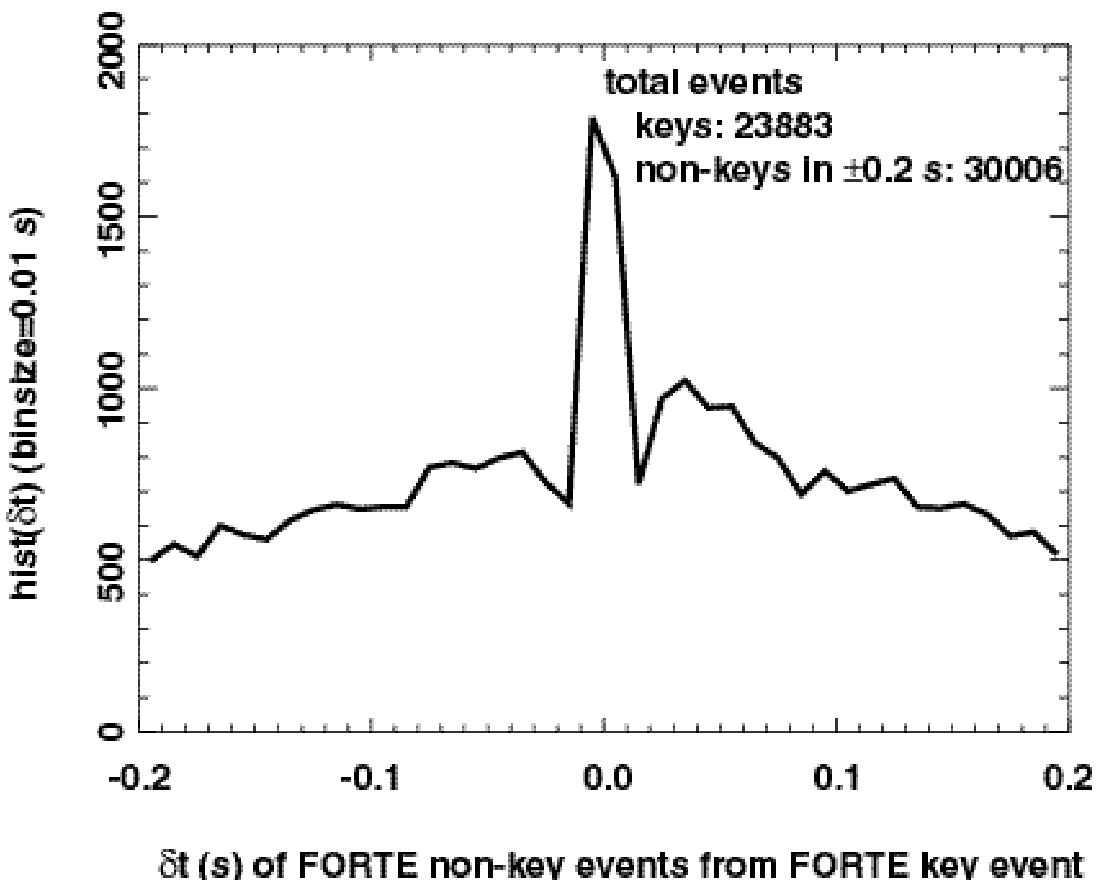


Given a FORTE event, what is the time-separation to other FORTE events? Shown here are time-separation distributions for global (top) and CONUS (bot) events during June 1998. The global event set contains 197,388 events. On average, there are more than 2 neighbors within ±200 ms. The CONUS event set contains only 9,375 events. On average, there are about 0.2 neighbors within ±200 ms. This shows the effect of higher trigger-level biases over the CONUS, imposed by higher anthropogenic radio noise (see previous figure).

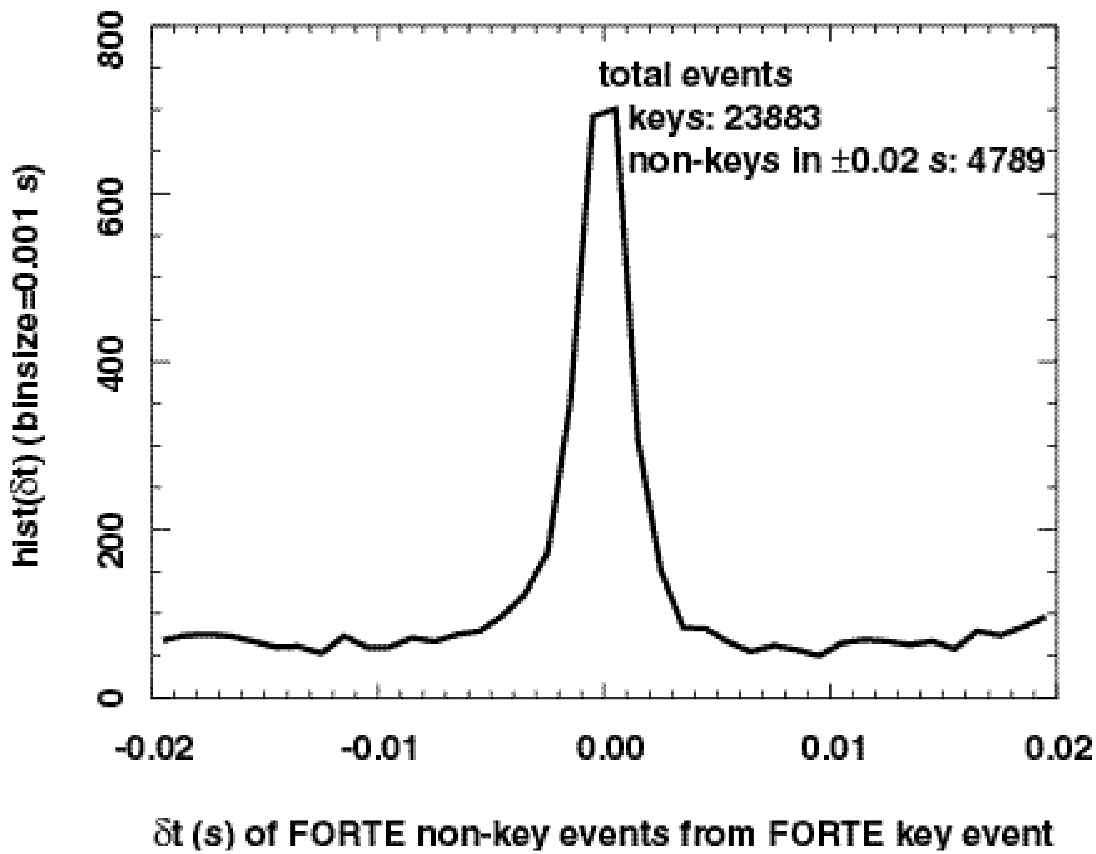


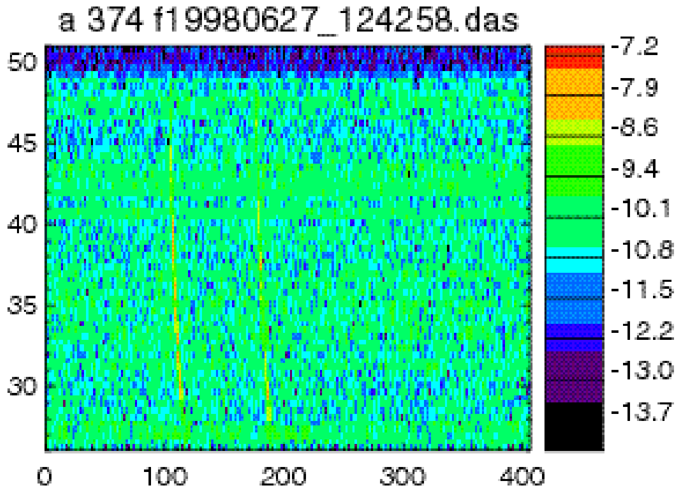
For the same data plotted in previous figure, this shows the distribution of *number of neighbors* within ±200 ms, for global (top) and CONUS (bot) events during June 1998. It is clear that the two distributions differ qualitatively, with the FORTE events detected over the CONUS relatively isolated and bereft of neighboring events. This likewise shows the effect of higher trigger-level biases over the CONUS, imposed by higher anthropogenic radio noise (see previous figure).

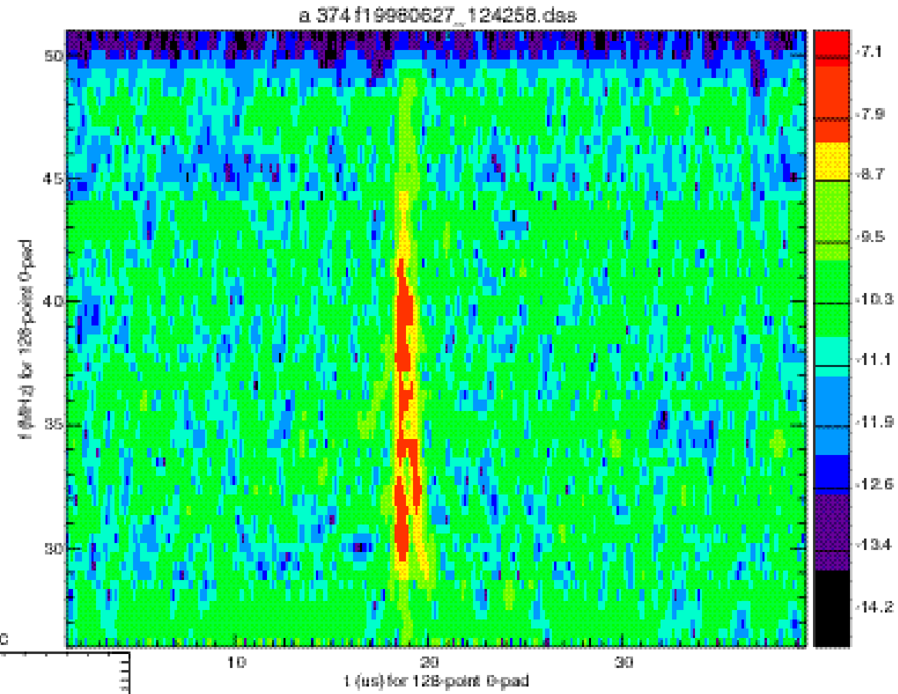
Neighbor time-separation distribution relative to the NLDN-coincident FORTE VHF events. These events are skewed by both being coincident with NLDN and being detected in the radio-noisy CONUS. The most likely neighboring events are within ±10 ms. There is on the order of 1 neighbor event in ±200 ms.

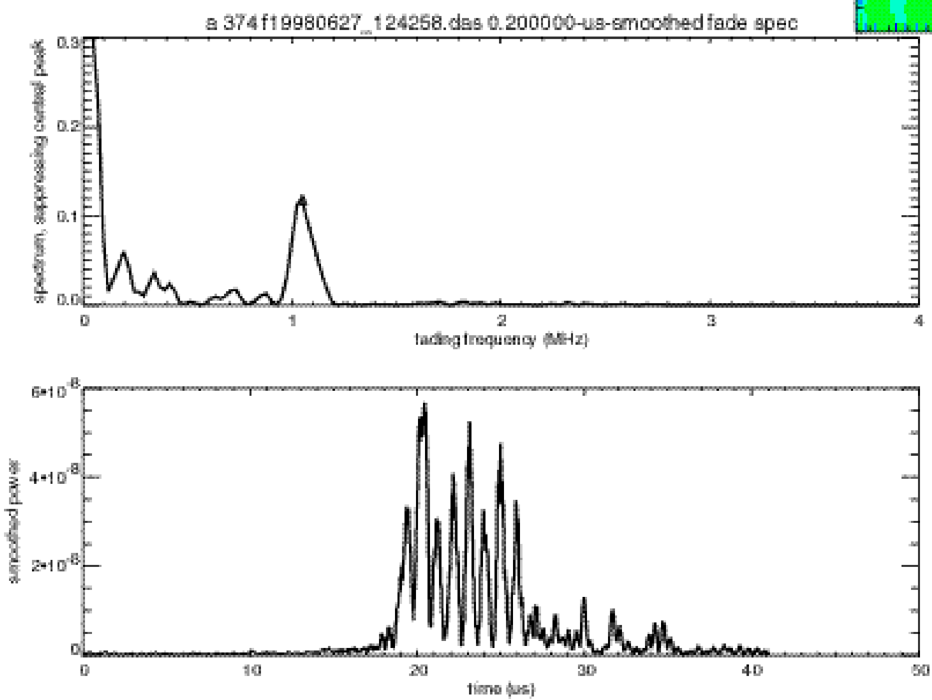


Neighbor time-separation distribution relative to the NLDN-coincident FORTE VHF events, as previously, but now zoomed onto central ±20 ms. The most likely neighboring events are within ±3 ms. There is on the order of 0.2 neighbor event in ±20 ms. The conclusion of this and the previous figure is that for a FORTE event coincident with an NLDN stroke, there is unlikely to be more than 1 neighboring FORTE event which can be associated with the same flash.



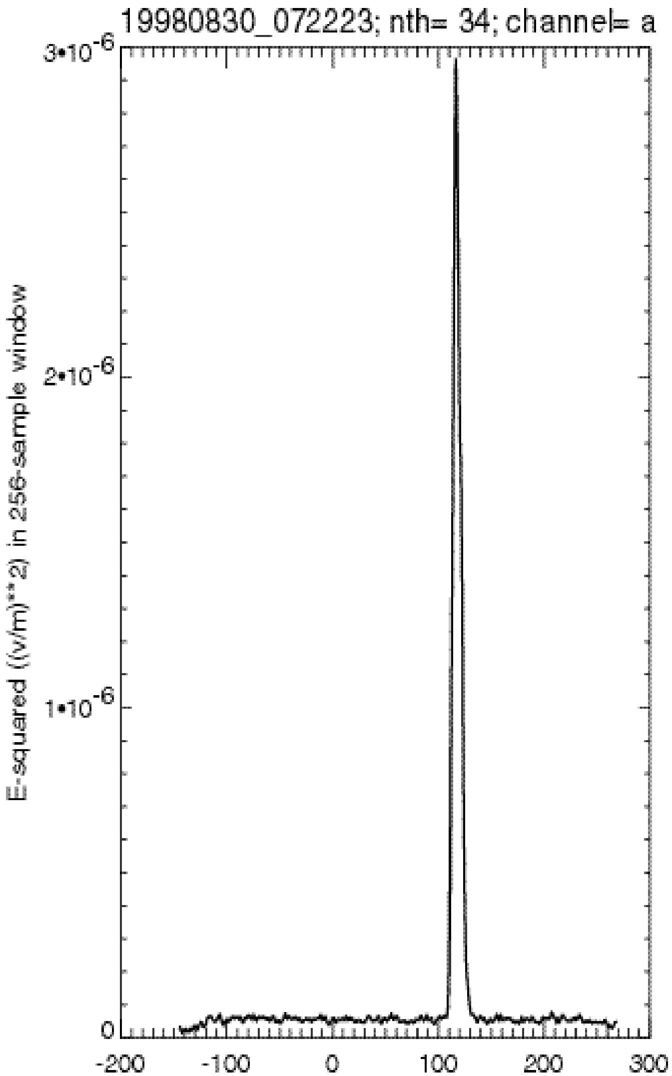


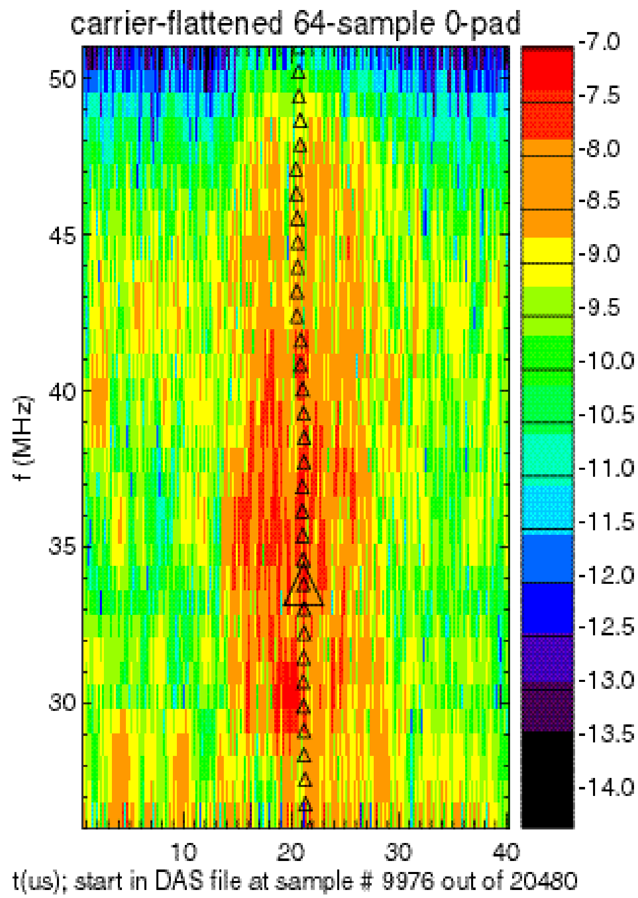




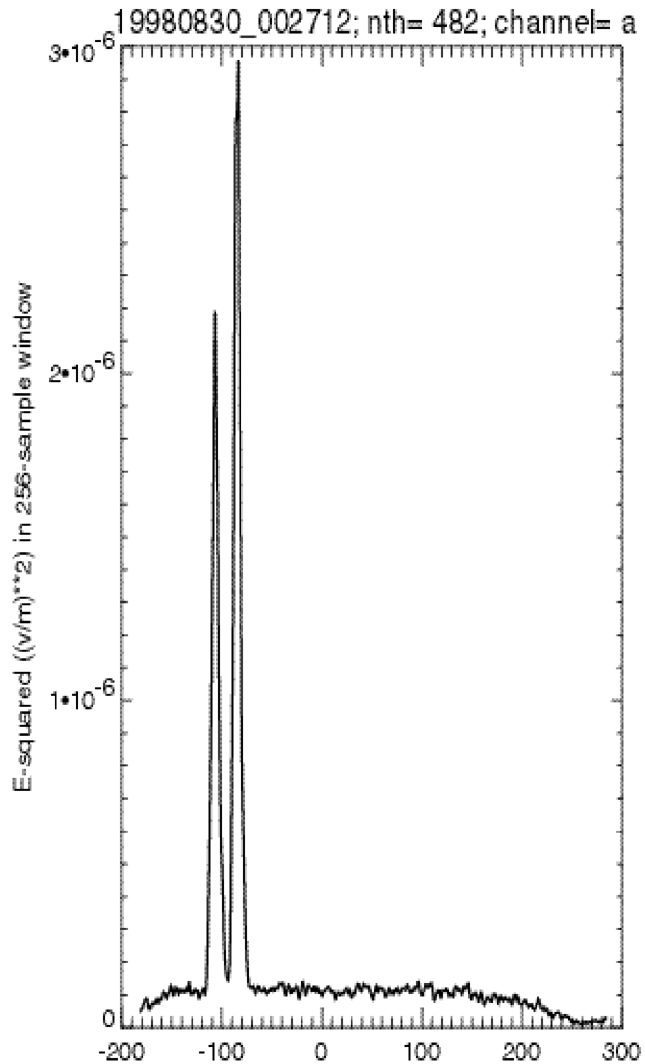
First, this shows the kind of FORTE VHF event which is *rarely or never* closely coincident with an NLDN stroke. This is a narrow-pulse plus a ground reflection (narrow bipulse). Upper left: periodogram of bipulse. Upper right: Zoom on first pulse, after first-order dechirping, showing submicrosecond structure. Lower left: Spectrum (top panel) and time series (lower) of 200-ns smoothed power, showing polarized fading.

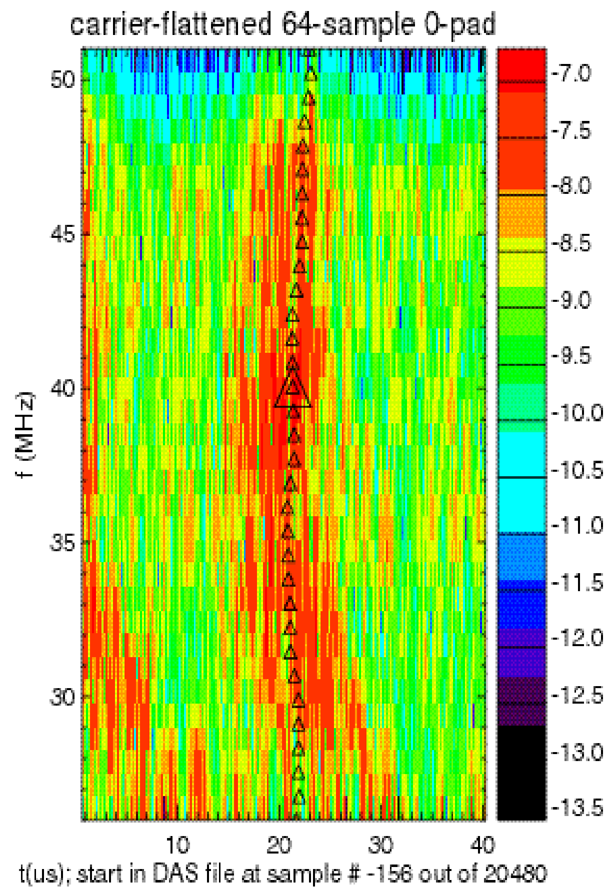
Power envelope (left) and zoomed periodogram (right) for typical "wide monopulse" FORTE VHF signal. Lack of a second pulse indicates the source's proximity to the ground. Typical pulsewidths are on the order of 10 μs. The pulse is incoherent over time and frequency. These are particularly likely to be coincident with NLDN *positive* CGs. In this and all subsequent periodograms, the signal has been pre-corrected for the first-order ionospheric dispersion.



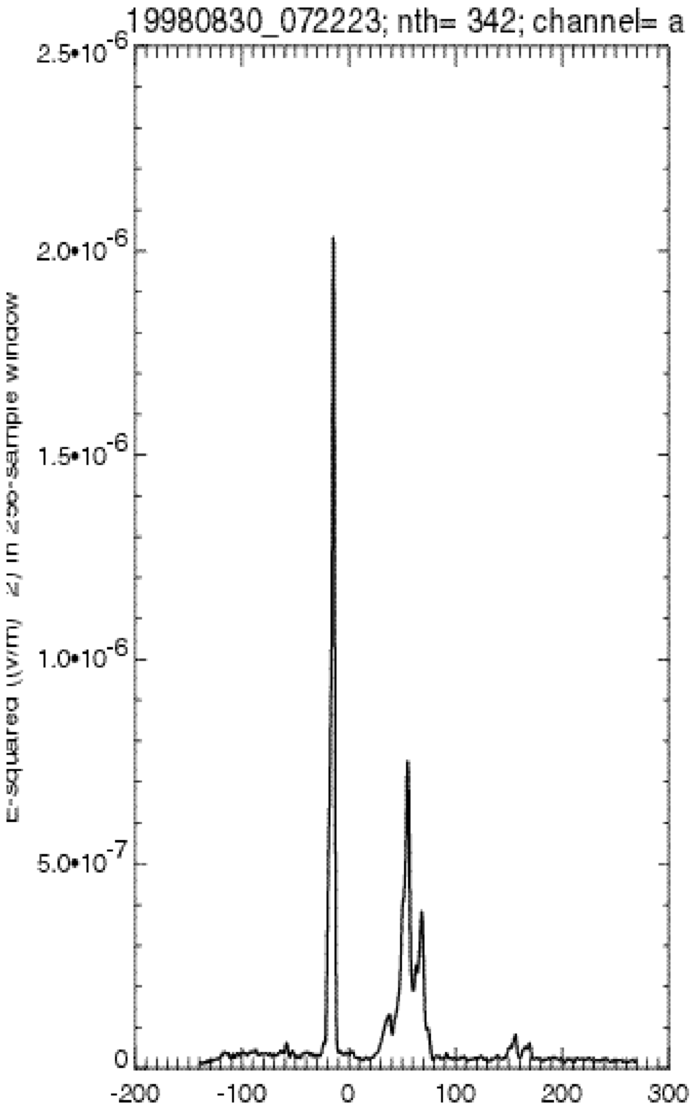


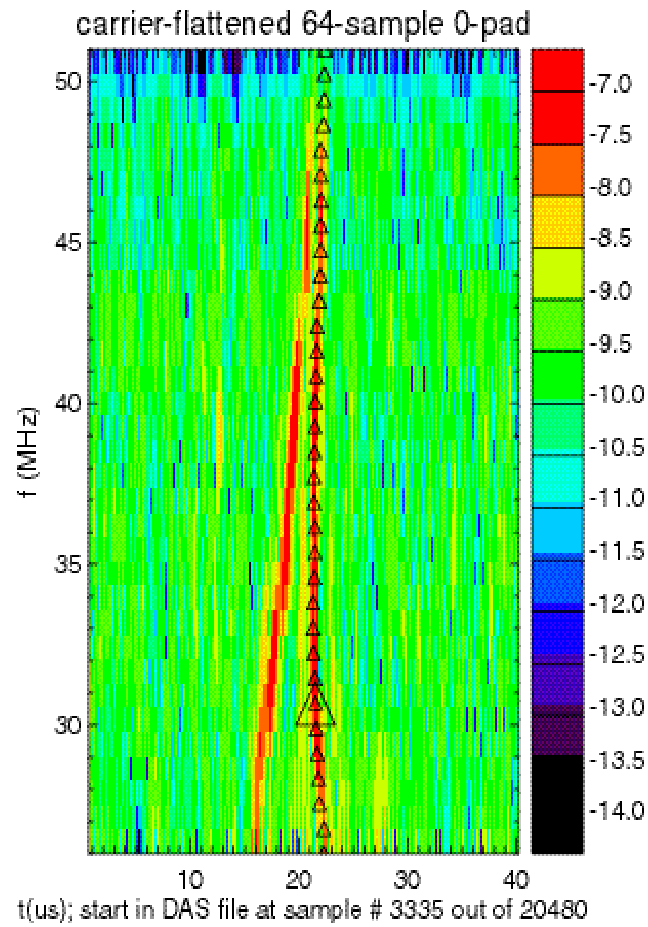
Power envelope (left) and zoomed periodogram (right) for typical “wide bipulse” FORTE VHF signal. The second pulse is from a ground reflection. Like the “wide monopulse”, the signal is incoherent in both time and frequency, and the intrinsic pulsewidth is on the order of 10 μs. Such VHF signals can be coincident with all types of NLDN-detected strokes. Narrower bipulses are common in FORTE data but are only rarely coincident with NLDN-detected strokes. This is probably because the narrower bipulses are associated with purely intracloud processes.



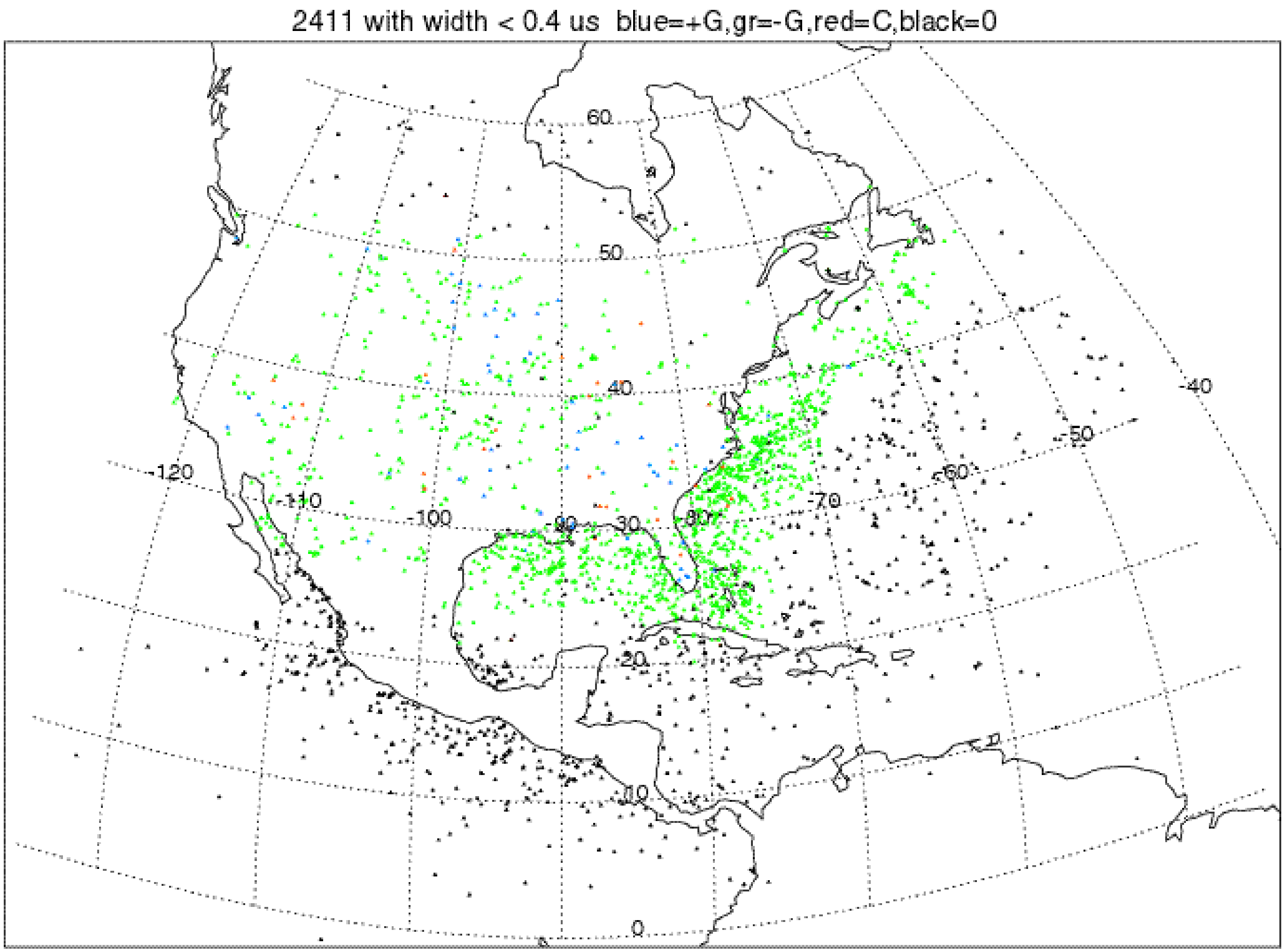


By contrast with the incoherent signals shown in the last two figures, there is a remarkably coherent, extremely narrow (<200 ns) emission associated exclusively with *negative* CGs. (The extremely narrow pulse is split by ionospheric birefringence.) This narrow pulse occurs at the time of attachment and is tightly coincident (typically within 10 μs) with the corresponding NLDN -CG. (Separations on this order cannot be distinguished from zero, given uncertainties in satellite position.) These pulses do not show a ground reflection; they are at ground (water).

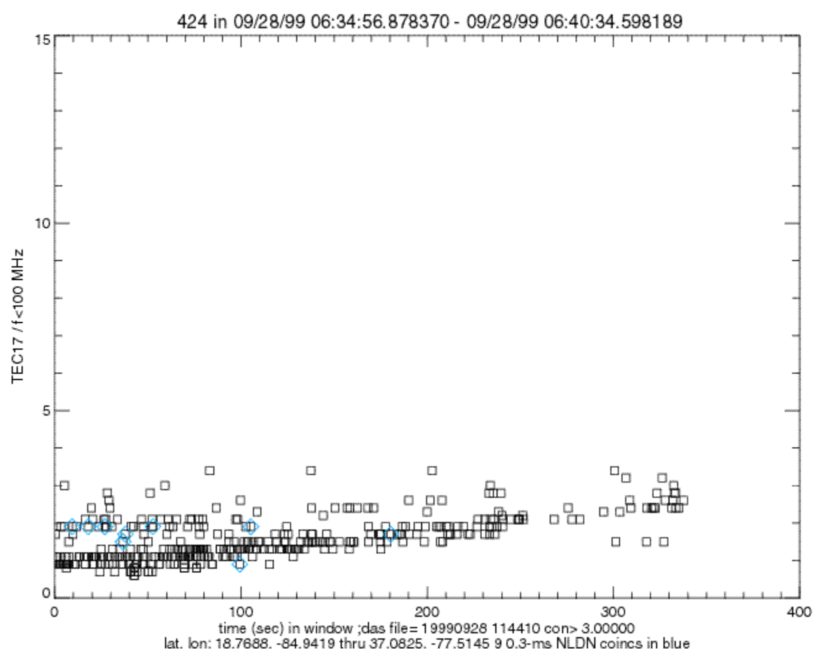


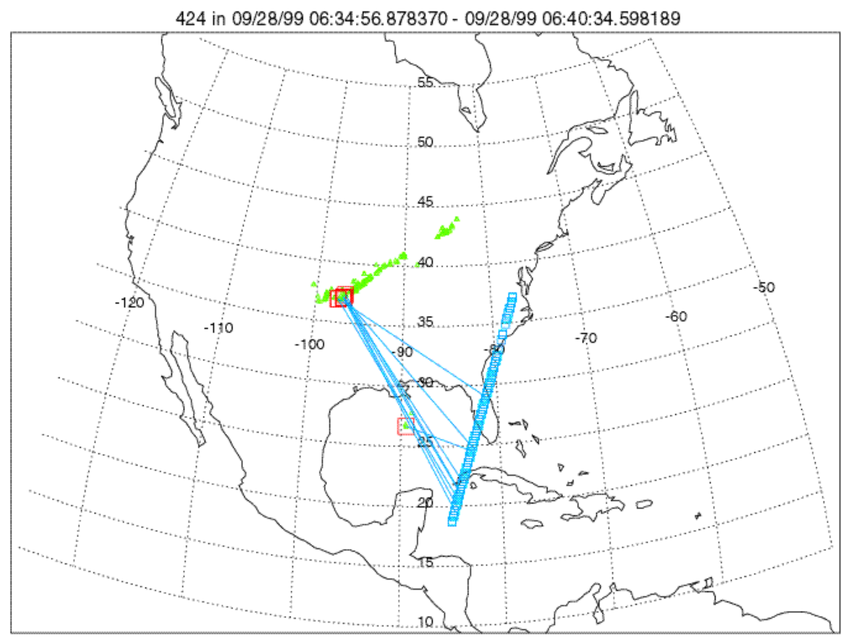


Position of all NLDN strokes coincident with the ultranarrow pulses (see previous figure). Note the nearly exclusive role of *negative* CGs for the strokes which can be identified by NLDN. These FORTE ultranarrow events are 5 times more likely to be associated with -CGs on seawater than with -CGs on land. They are essentially absent with *positive* CGs.



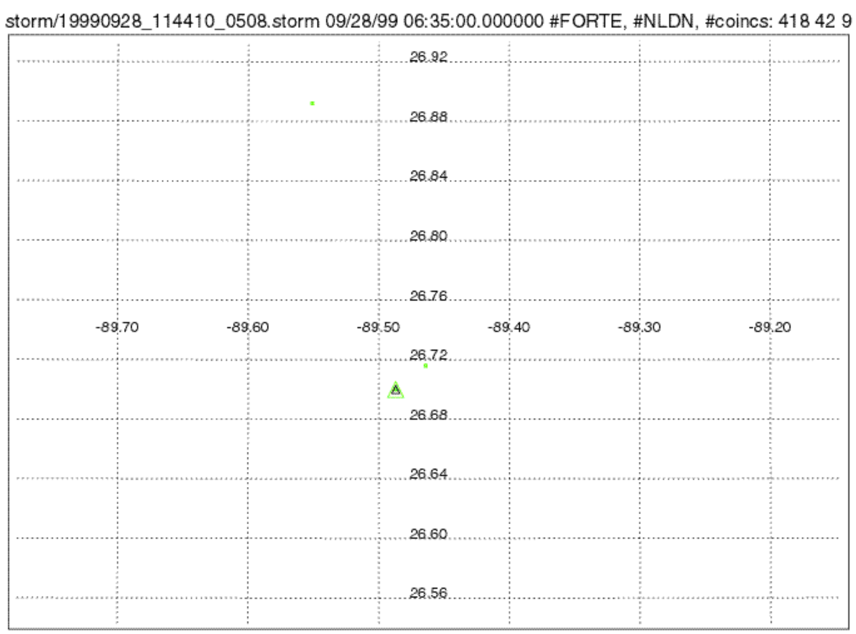
Example1: NLDN-detected storms in both the Midwest/Great Plains and the Gulf of Mexico are accompanied by coincident VHF signals recorded by FORTE during an ascending pass. On the left is shown the total electron content (TEC) versus time during the pass, indicating the presence of two distinct zones whose VHF emissions are detected by FORTE. The more distant zone gives rise to the higher TEC (due to a longer slant path through the ionosphere.) In this case the more distant storm is that in the Midwest/Great Plains. Note that (1) a minority of the FORTE detections (indicated by TEC data) are coincident (as indicated by blue symbols on left) with NLDN, and (2) this is less so for the continental storm, and more so for the marine storm. This illustrates the general observation that most FORTE VHF signals are noncoincident with NLDN strokes, and vice versa. This is due to the fact that much of the VHF signal set dervives from in-cloud processes, which are less amenable (relative to CG) to NLDN detection.



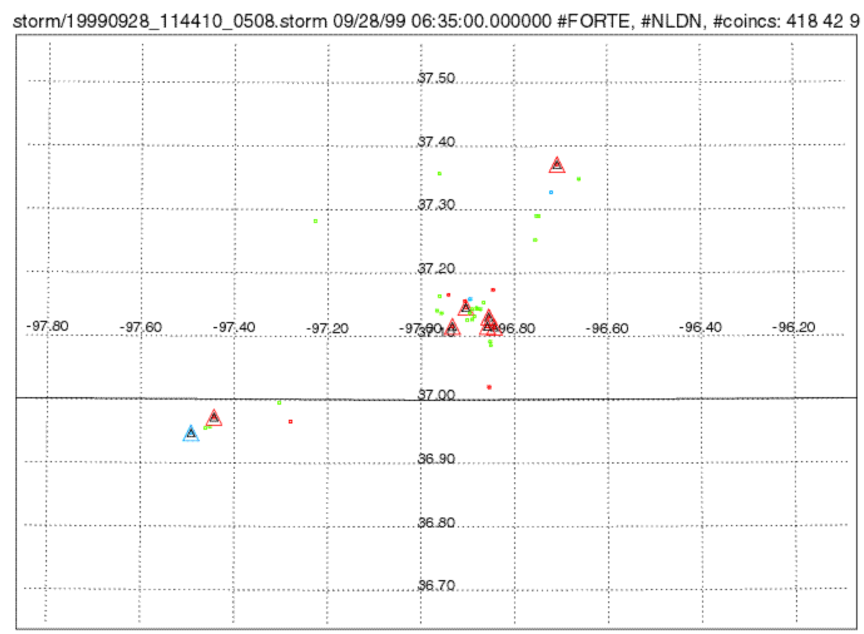


Example 1 (continued): Zoomed maps of selected portions of NLDN stroke set for the FORTE pass. Small symbols indicate NLDN strokes, with green for -CG, blue for +CG, red for IC. The larger triangle and black dot indicate corresponding FORTE-coincident NLDN-detected strokes. The storm in the Gulf (left panel below) has just a few strokes, all -CG, and only one of these is coincident with a FORTE VHF signal. On the other hand, that storm (see previous figure) provides copious FORTE signals, but most of these are not coincident with NLDN strokes. By contrast, the continental storm (right panel below)has -CG, +CG, and IC strokes, and the several FORTE coincidences are exclusively with the +CG and IC strokes. This is typical of FORTE coincidences: that given FORTE VHF signals are far more likely to coincide with +CG/IC strokes detected by NLDN, and furthermore, are even more likely to coincide with no strokes detected by NLDN, presumably due to the predominantly IC origin of VHF emissions.

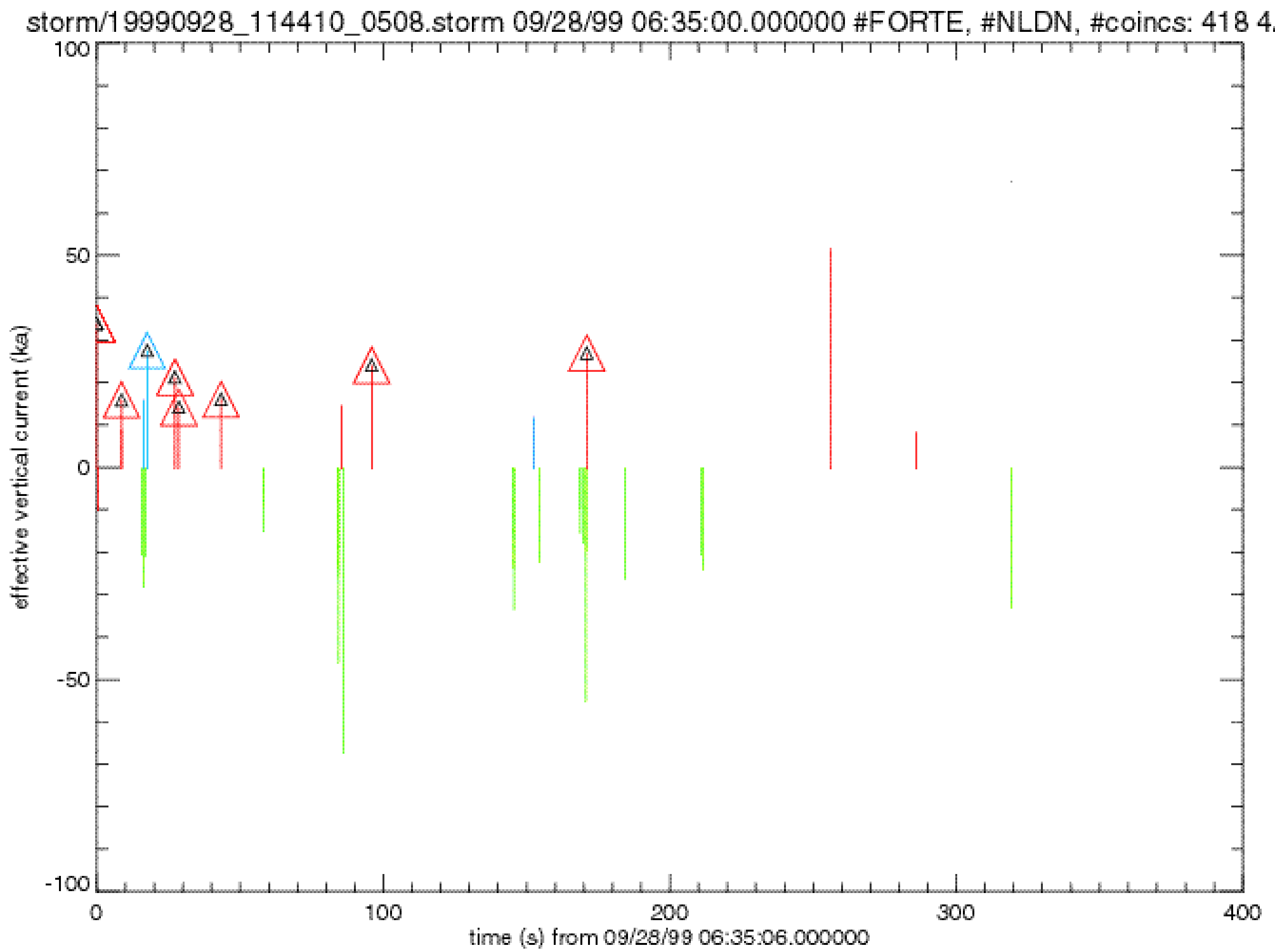
Storm in Gulf of Mexico



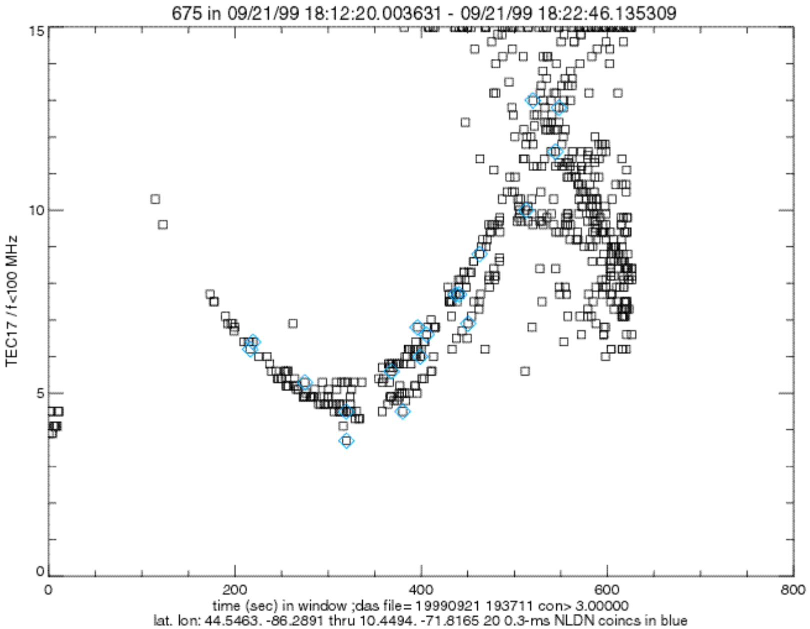
Storm in Midwest/Great Plains

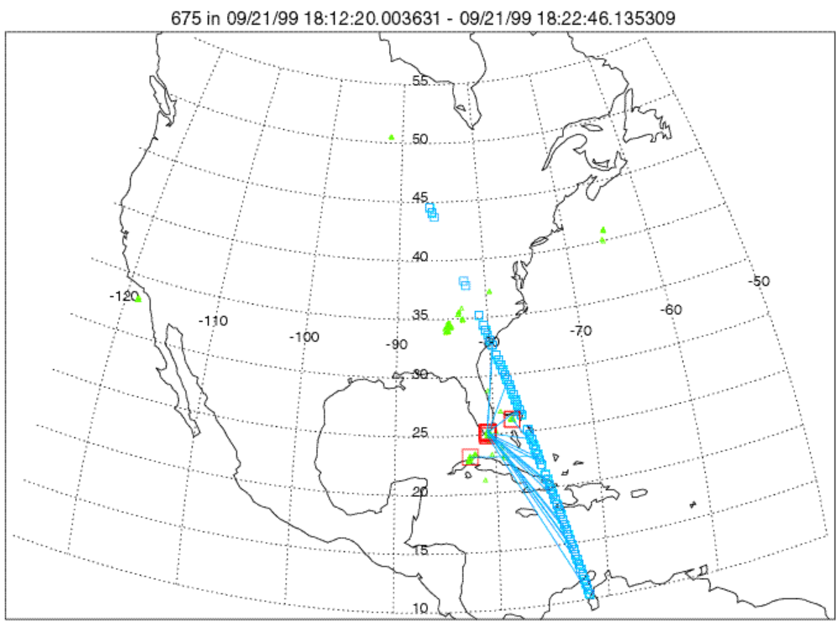


Example 1 (continued): NLDN-determined effective vertical current vs time for strokes in the continental zoom box (see previous figure, right panel). The IC currents (red) are not quantitatively meaningful, but the +CG (blue) and -CG (green) currents are. The large triangles with inscribed black triangles are FORTE-coincident strokes. This illustrates the tendency for FORTE/NLDN coincidences to occur preferentially in storms with significant +CG or IC content.

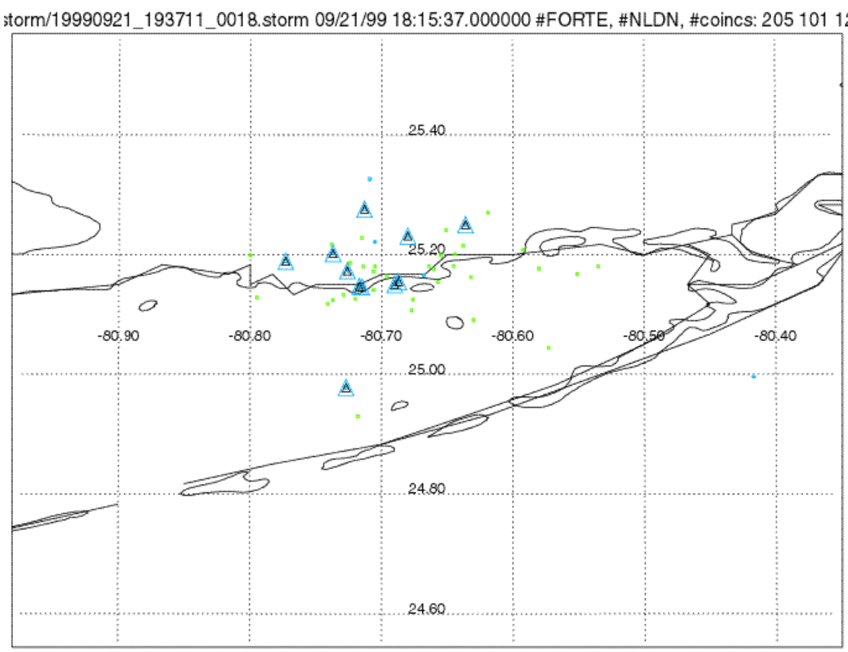


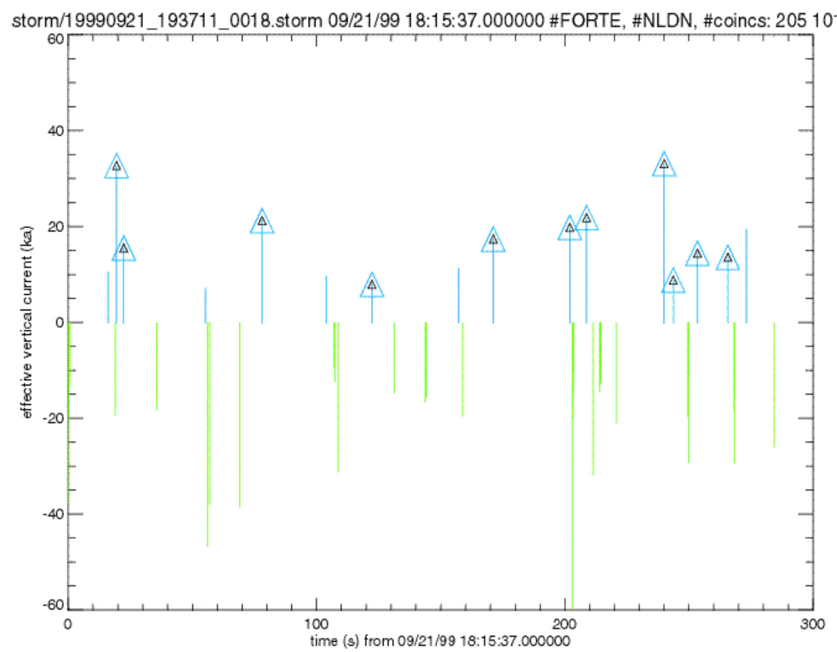
Example 2: Intense air-mass thunderstorm at the southern tip of Florida with several FORTE VHF coincidences detected on a single pass. On the left is shown the TEC, and on the right the satellite pass map. The lower-TEC curve is from the nearer storm east of Florida, while the upper-TEC curve, further from the satellite, is from the storm which is zoomed in the next figure. Although there are several FORTE coincidences (blue symbols in left panel), there are far more VHF events lacking close NLDN coincidences but clearly from the same storm. This illustrates again the tendency of NLDN (efficient at detecting ground strokes) and FORTE (efficient, though to an extent as yet unquantified, in detecting VHF emissions from in-cloud processes) to emphasize complementary aspects of a lightning.



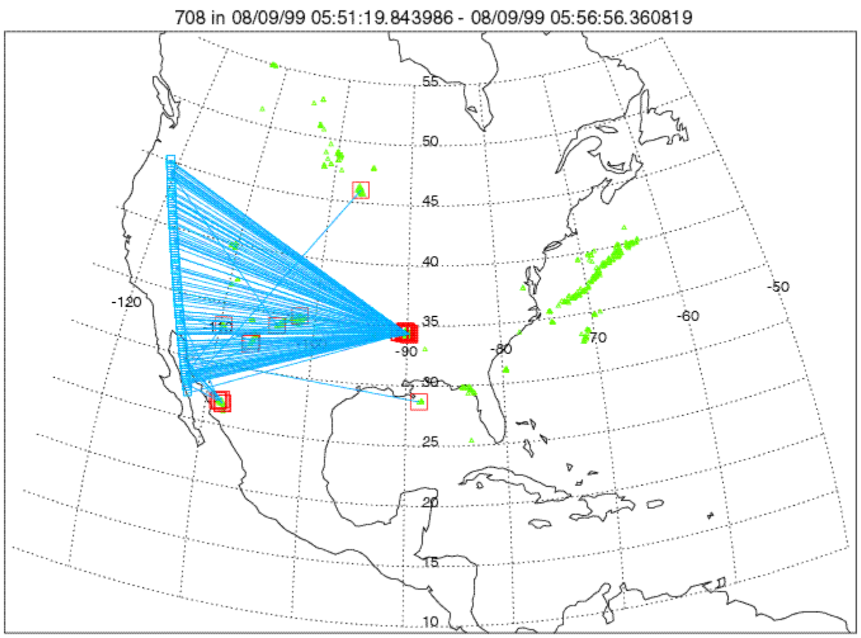


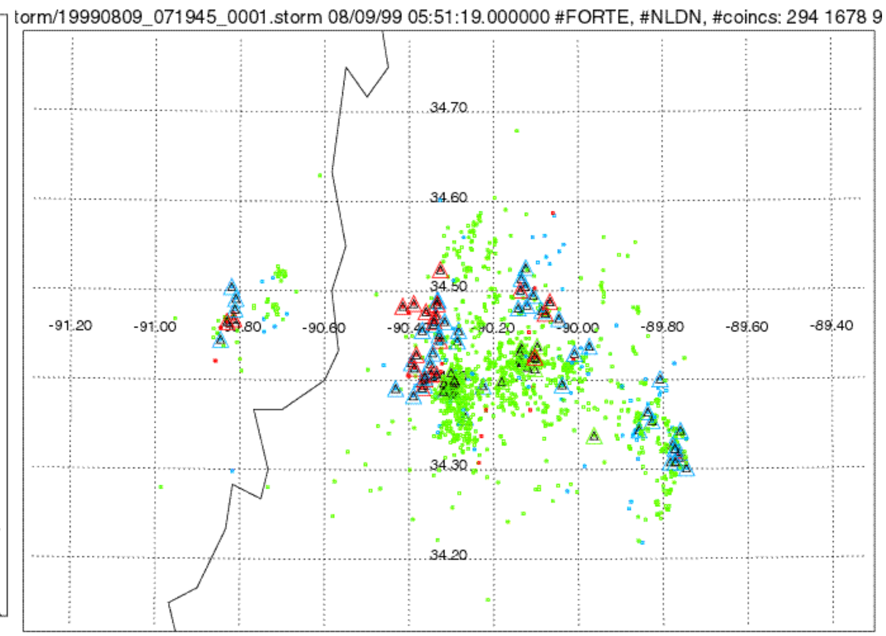
Example 2 (continued): Zoomed map (left panel) of southern Florida storm, NLDN-determined effective vertical current (right panel). Green=-CG, blue=+CG. Large triangles with inscribed black triangles indicated FORTE-coincident strokes. This illustrates again (see Example 1 above) the tendency of FORTE VHF to be coincident more often with +CG strokes than with -CG strokes. Moreover, storms with a significant fraction of +CG strokes tend to be detected overall by FORTE VHF coincidences. (By contrast, continental storms with only -CGs are less likely to feature FORTE-coincident strokes.)



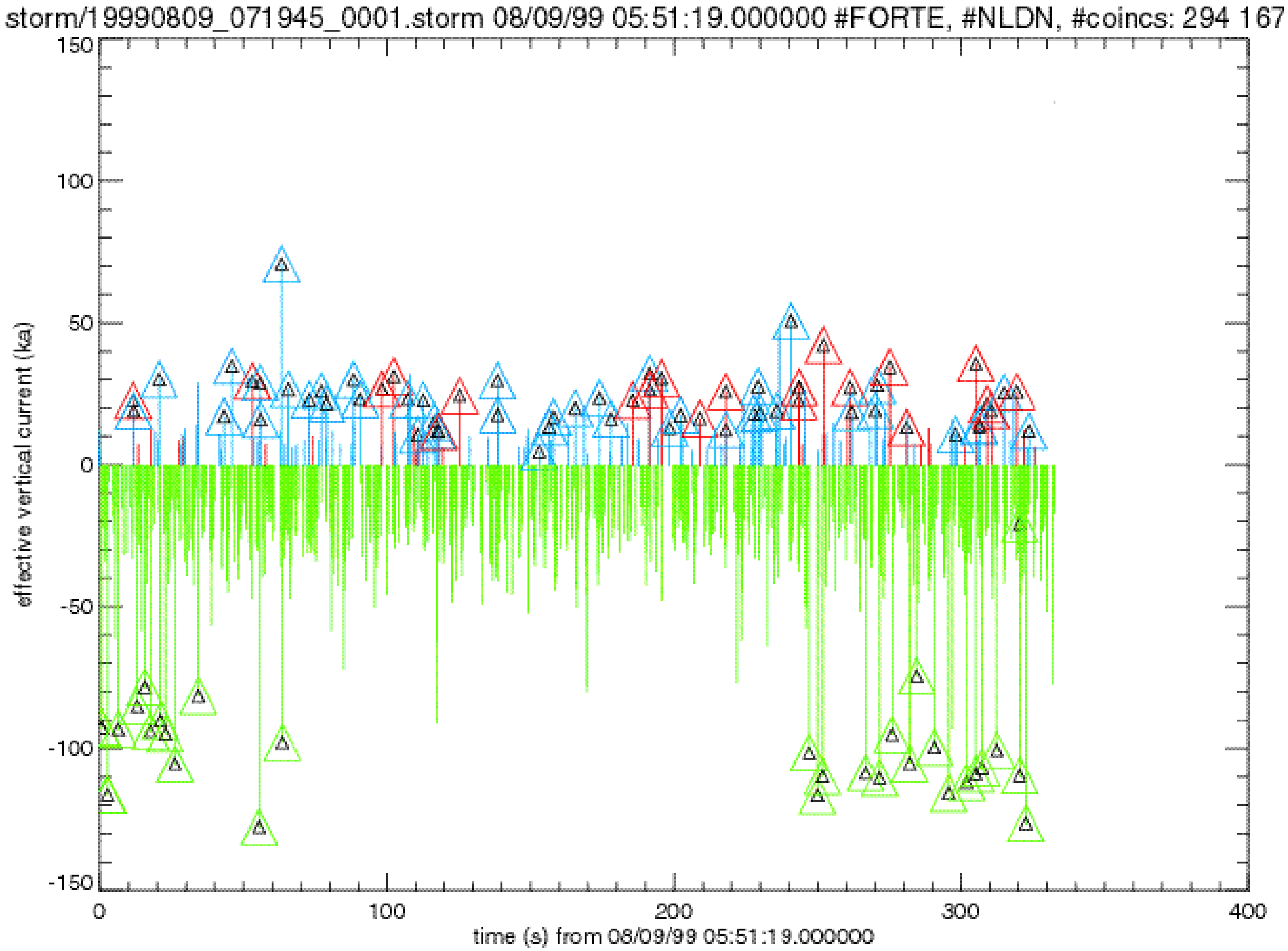


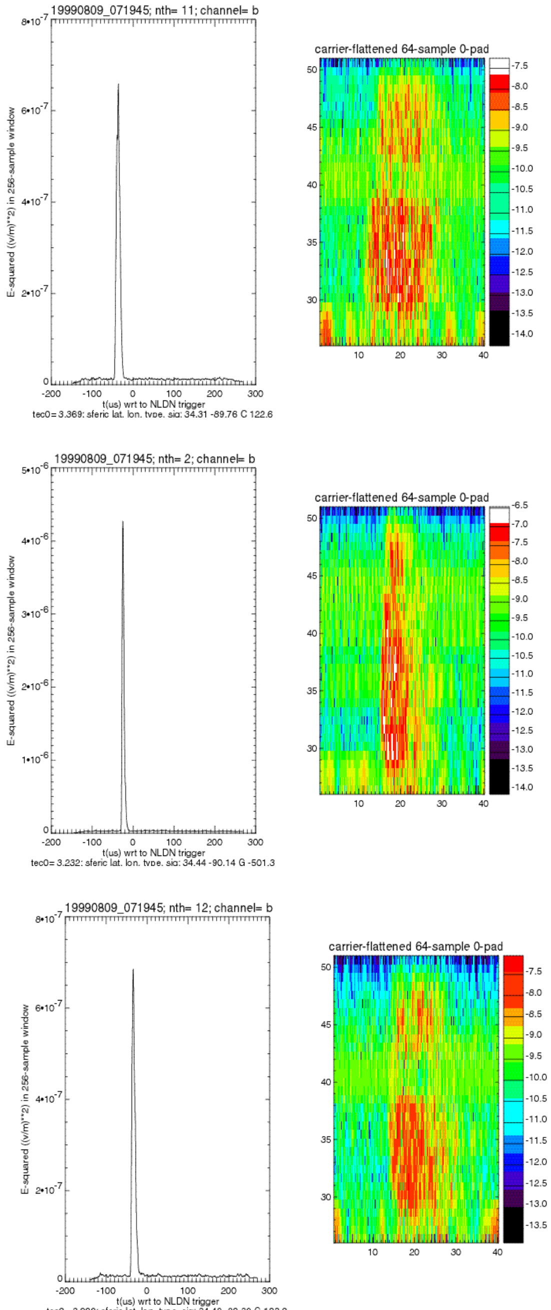
Example 3: Intense storm complex with core of -CGs and localized flanks of both +CGs and ICs. The large triangles, indicating strokes with coincident FORTE VHF events, occur mainly, though not exclusively, for +GCS and ICs. Intense, high-flash-rate, significantly +CG storms of this type appear to reliably engender coincidence with FORTE VHF.





Example 3 (continued): NLDN-determined effective vertical current vs time for strokes in the continental zoom box (see previous figure, right panel). The IC currents (red) are not quantitatively meaningful, but the +CG (blue) and -CG (green) currents are. The large triangles with inscribed black triangles are FORTE-coincident strokes. This illustrates that the FORTE-coincident -CG strokes are preferentially very-high-amplitude (> 50 kA). By contrast, the liklihood of FORTE coincidence for +GCs is indifferent to the current amplitude.





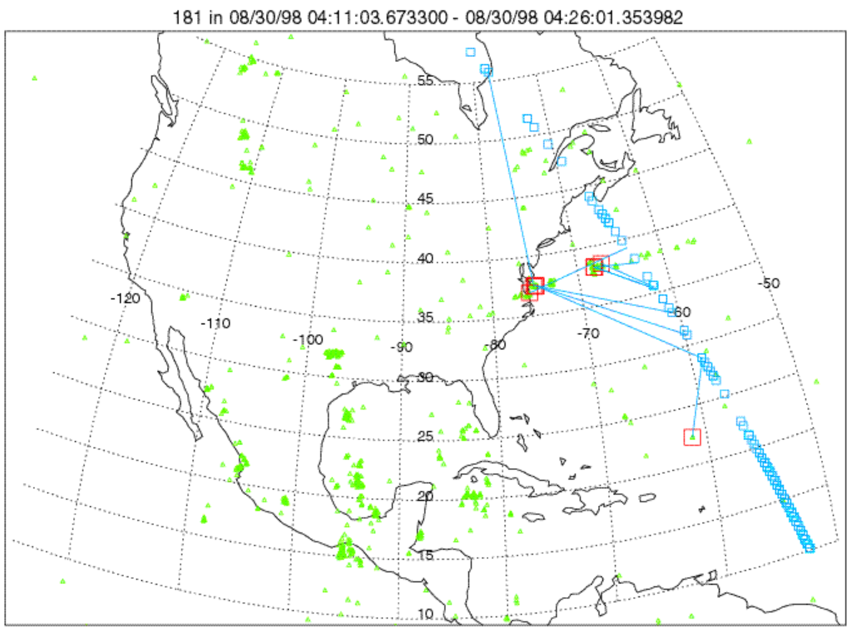
IC

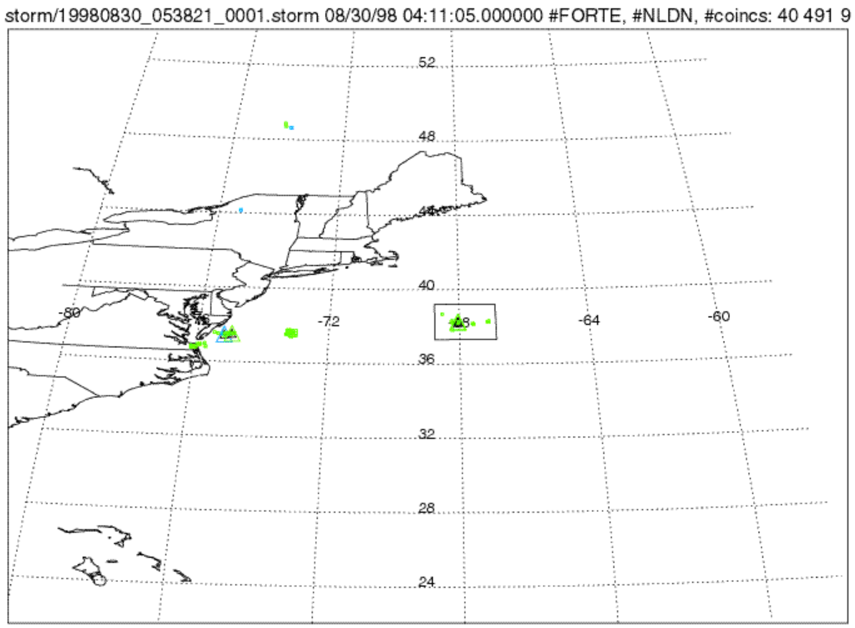
-CG

+CG

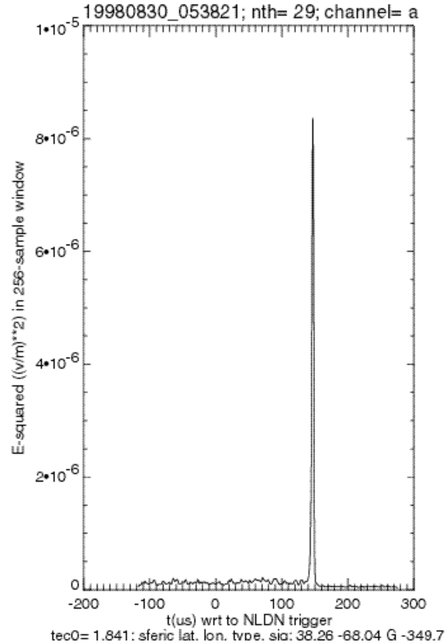
Example 3 (continued): In this intense storm with high flash rate and FORTE VHF events coincident with all amplitudes of +CG strokes but with only the highest amplitudes of -CG strokes, there is a tendency of the VHF signals to appear the same independent of whether associated with +CG, -CG, or IC strokes. This figure shows monopulses coincident with each flavor of NLDN stroke. There is not a large amount of difference between these three VHF signals; each is on the order of 10 μs wide; each is incoherent in both time and frequency. Similar parallels between bipulses associated with +CG, -CG, or IC strokes have been noted. The overall tendency is for NLDN-coincident FORTE VHF signals in this type of intense storm to differ very little according to the flavor of coincident stroke.

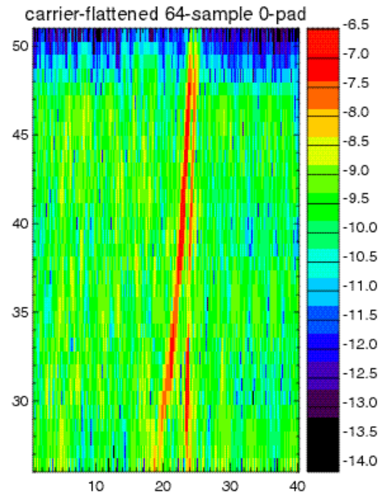
Example 4: Marine storms are more likely to be dominated by -CG strokes. Such storms on the continent would yield few coincident FORTE VHF events, but in the marine environment, these storms are typefied by a useable number of FORTE coincident detections. The pass map (left panel) shows a variety of small, low-intensity storms within view of the satellite. The event map (right panel) shows the zone that will be zoomed in the next two figures.

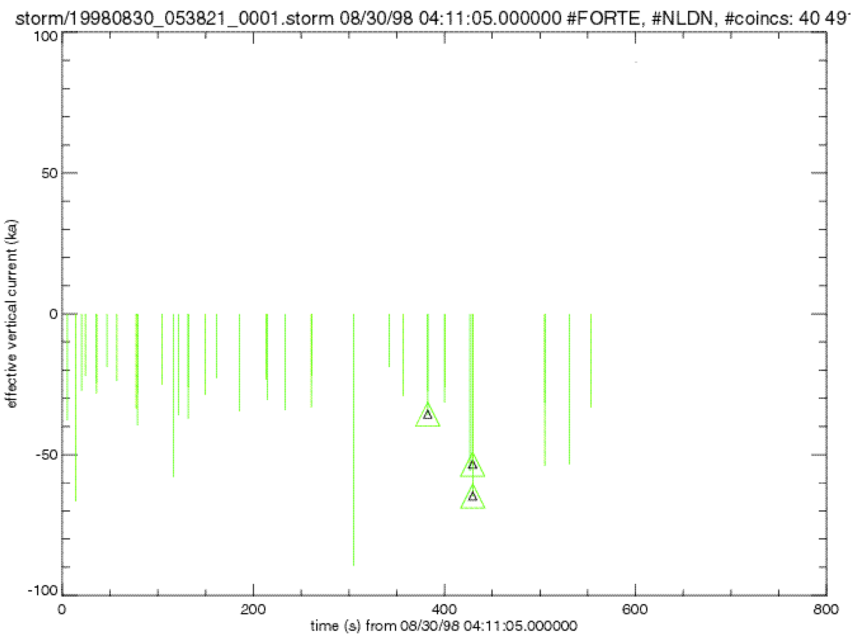


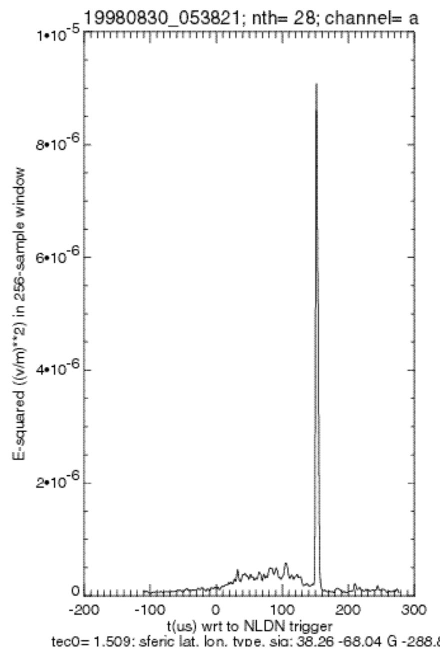


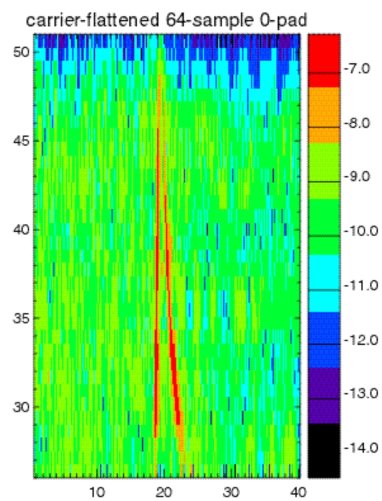
Example 4 (continued): Stroke amplitudes (left) and two (of total three) FORTE VHF signals (right). Characteristic of marine storms, the dominant stroke type detected by NLDN is -CG, and the VHF signal derives from the submicrosecond emission accompanying the onset of the return stroke. The three coincidences are associated with three of the higher-current strokes.



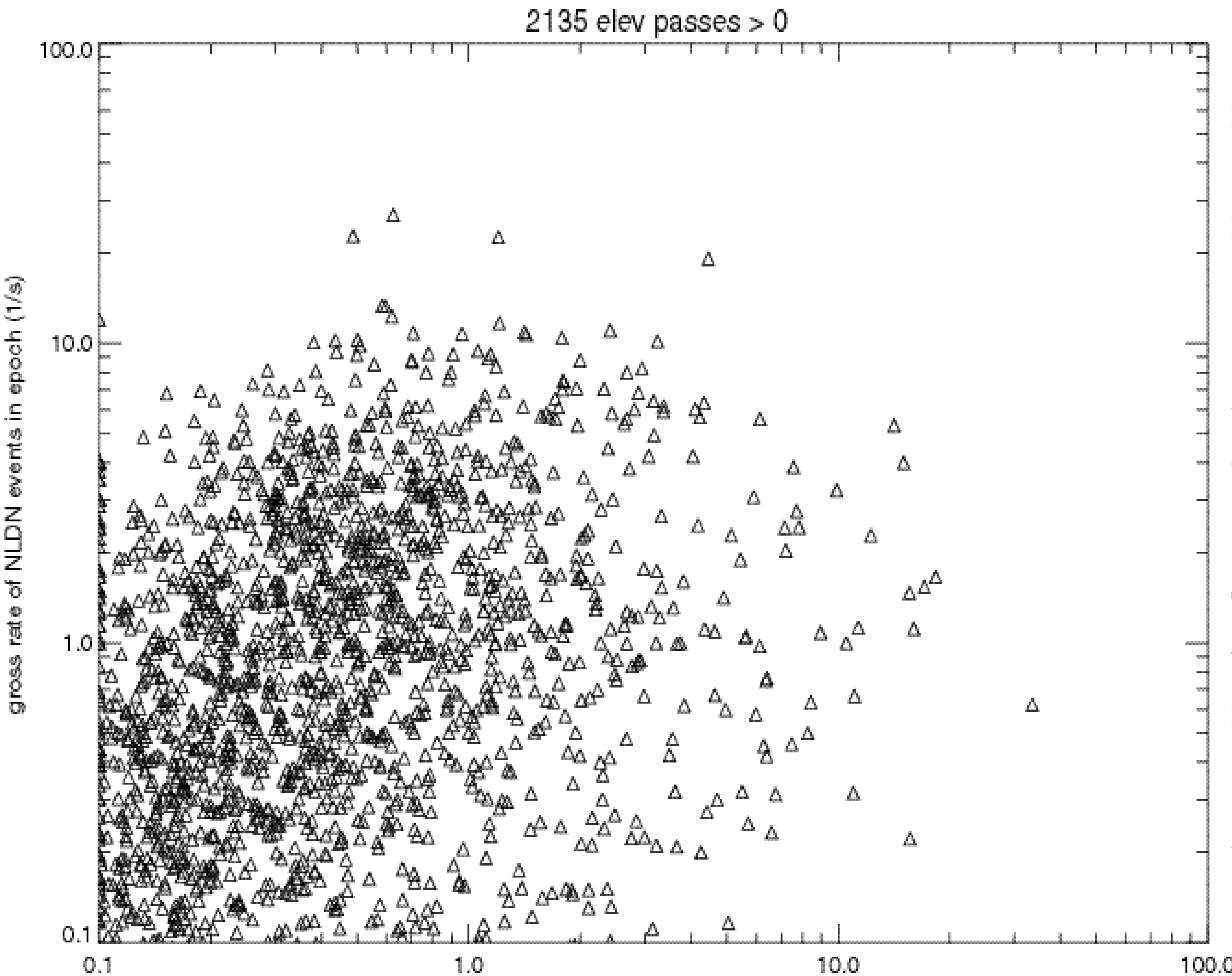






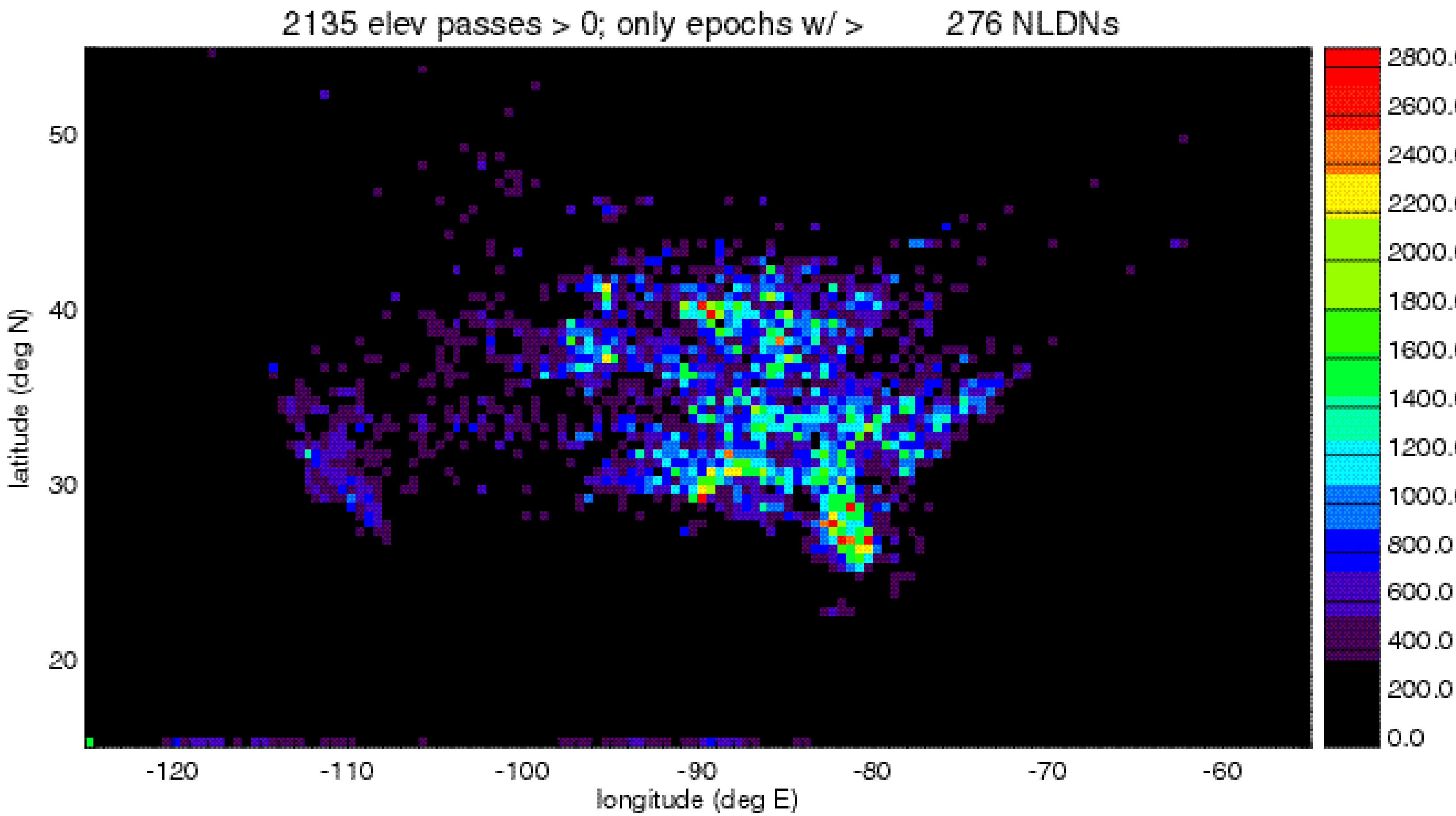


During the total of six months of 1998 & 1999 joint campaign, FORTE took 2135 individual passes during which (1) NLDN-reported stroke locations were geometrically visible to FORTE, and (2) FORTE was armed and recording signals. This and successive figures examine, somewhat more broadly than was done in the storm examples above, the statistical evidence on the relationship between the satellite VHF observations and the ground-based stroke detections provided by NLDN. The total of NLDN strokes visible to FORTE was 1.74 million.

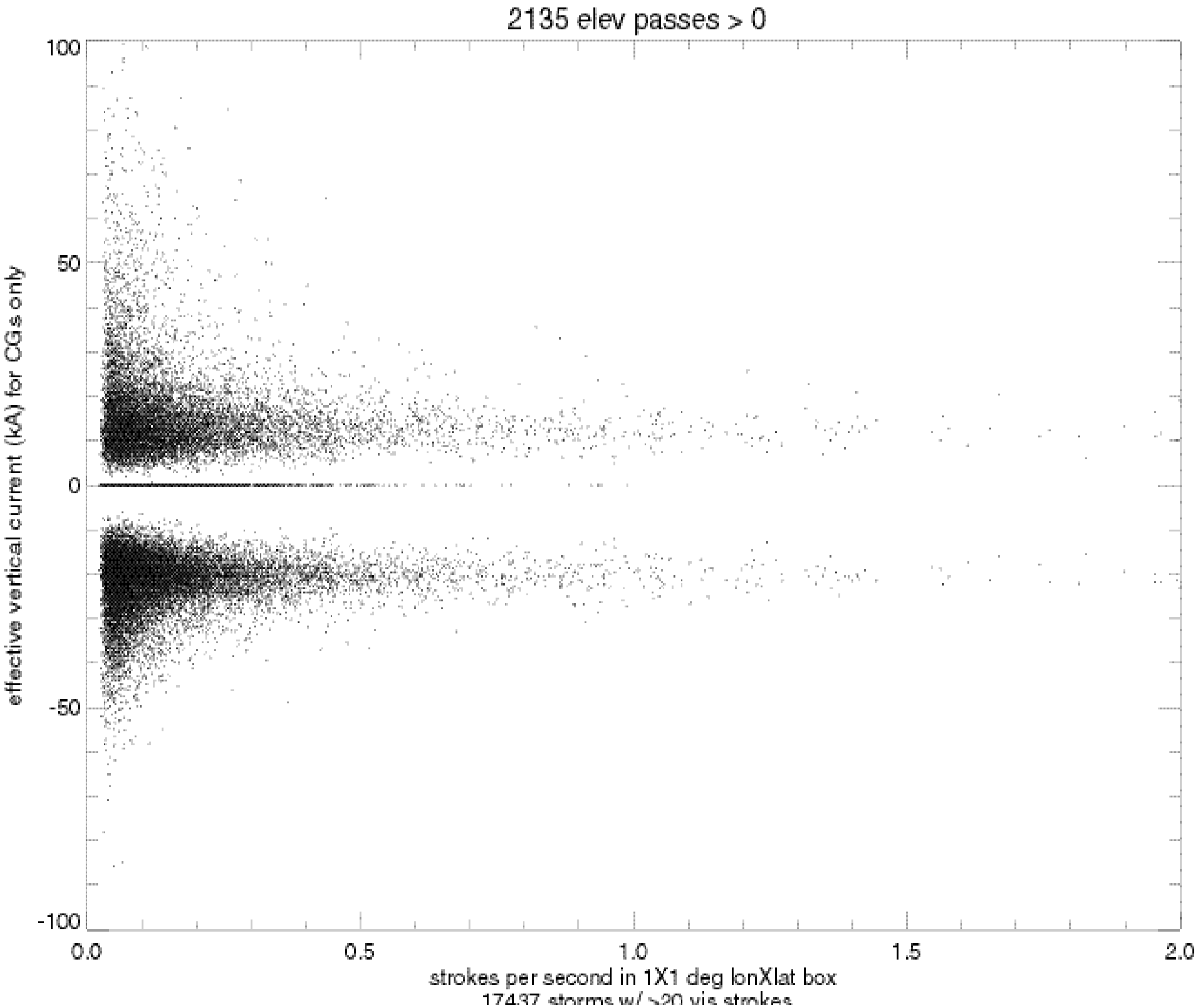


Comparison of gross rate of NLDN strokes (vertical) versus gross rate of FORTE VHF events (horizontal) for all 2135 satellite passes. All FORTE passes with <0.1 event/sec are collected on the left vertical axis. There is an overall tendency for there to be more FORTE events during active NLDN periods, but this is subject to very wide scatter.

During the 2135 FORTE passes, the mean number of NLDN events was 276. This figure shows the density of total NLDN in 1degX1deg stroke-location bins integrated over the FORTE passes having >276 NLDN events. Clearly Florida, the Southeast, and parts of the Midwest dominated the stroke set whose VHF manifestations would have been available for FORTE recording. The data shown here comprise most of the 1.74 million stroke locations visible to FORTE.

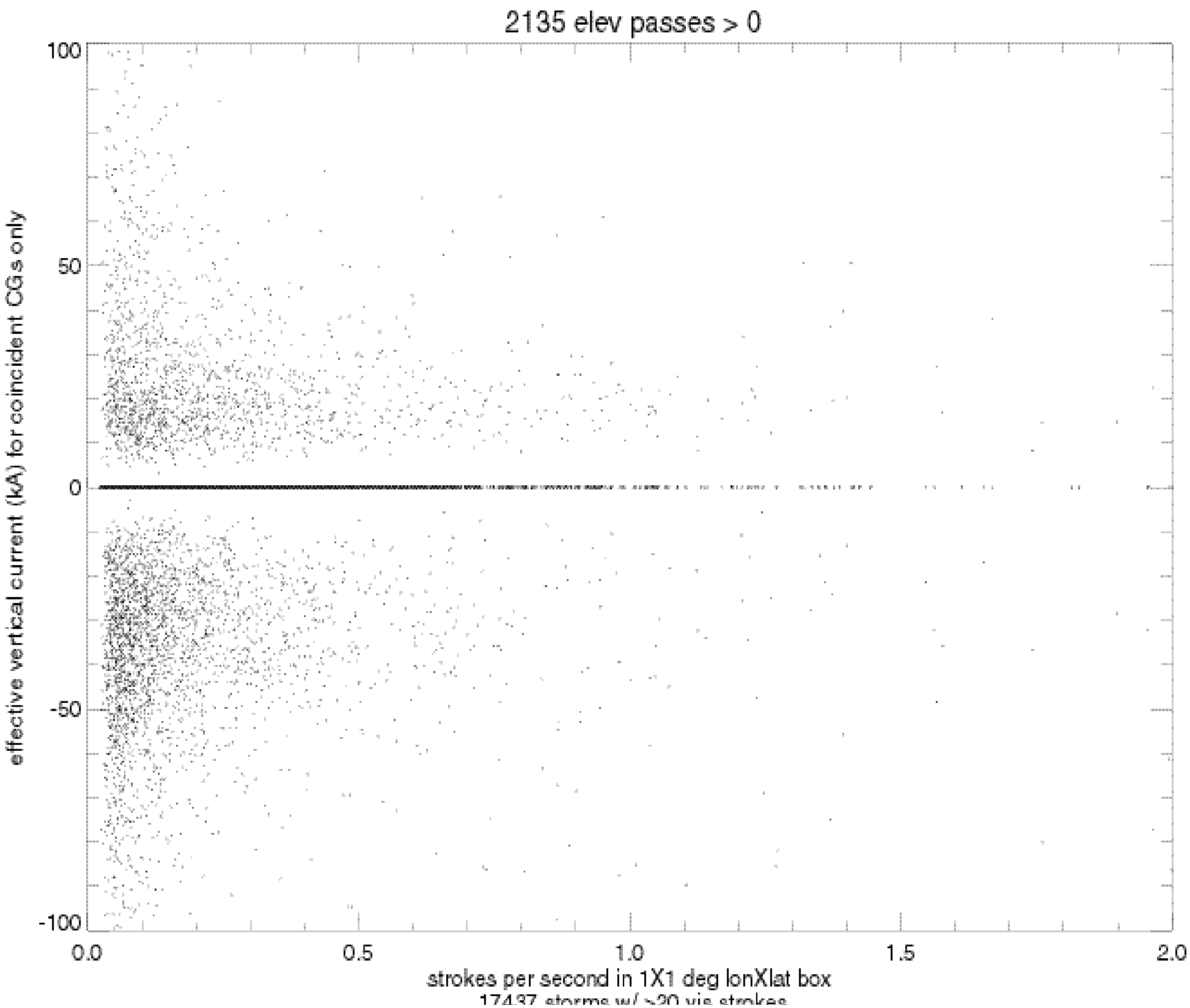


Within the 2135 FORTE passes in which NLDN strokes were visible, the per-pass stroke set was placed onto a map in 1degX1deg location bins, on 1/2 deg X 1/2 deg centers (50% overlap). Then, whenever a pass/location cell registered >20 NLDN strokes that were geometrically visible to FORTE, that pass/location was registered as a “storm”. Cumulatively, there were 17,437 such “storms”. This figure compares the NLDN-determined CG vertical current (vertical axis) averaged within each “storm”, to the stroke rate for that storm. FORTE coincidence *not* required.

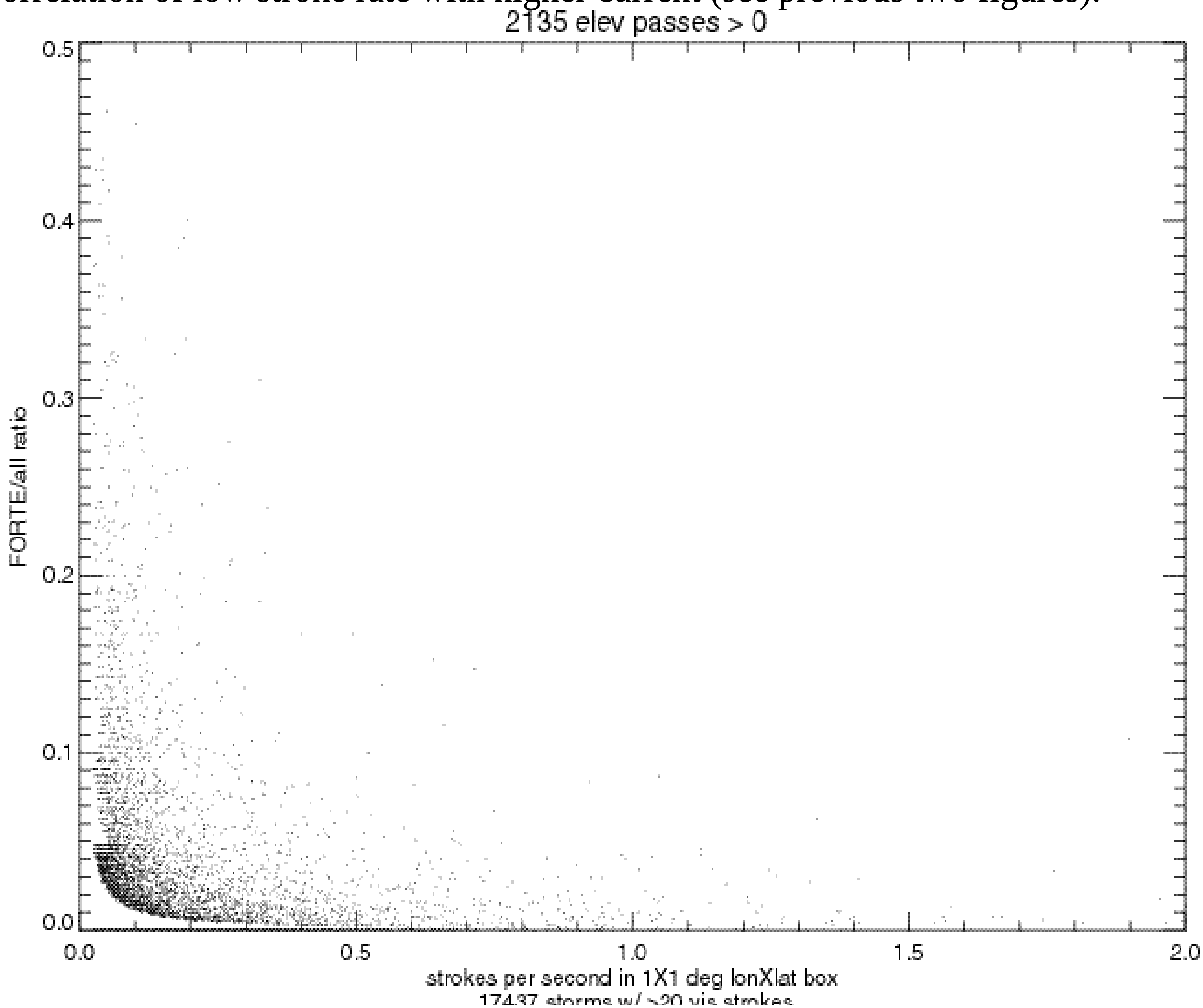


The +CG strokes are in the upper half, and the -CG strokes are in the lower. For both polarities of strokes, the highest-average-current storms are those with the lowest stroke rate. However, there is a slight rebound of the average current as the stroke rate is increased beyond 0.2 strokes/s.

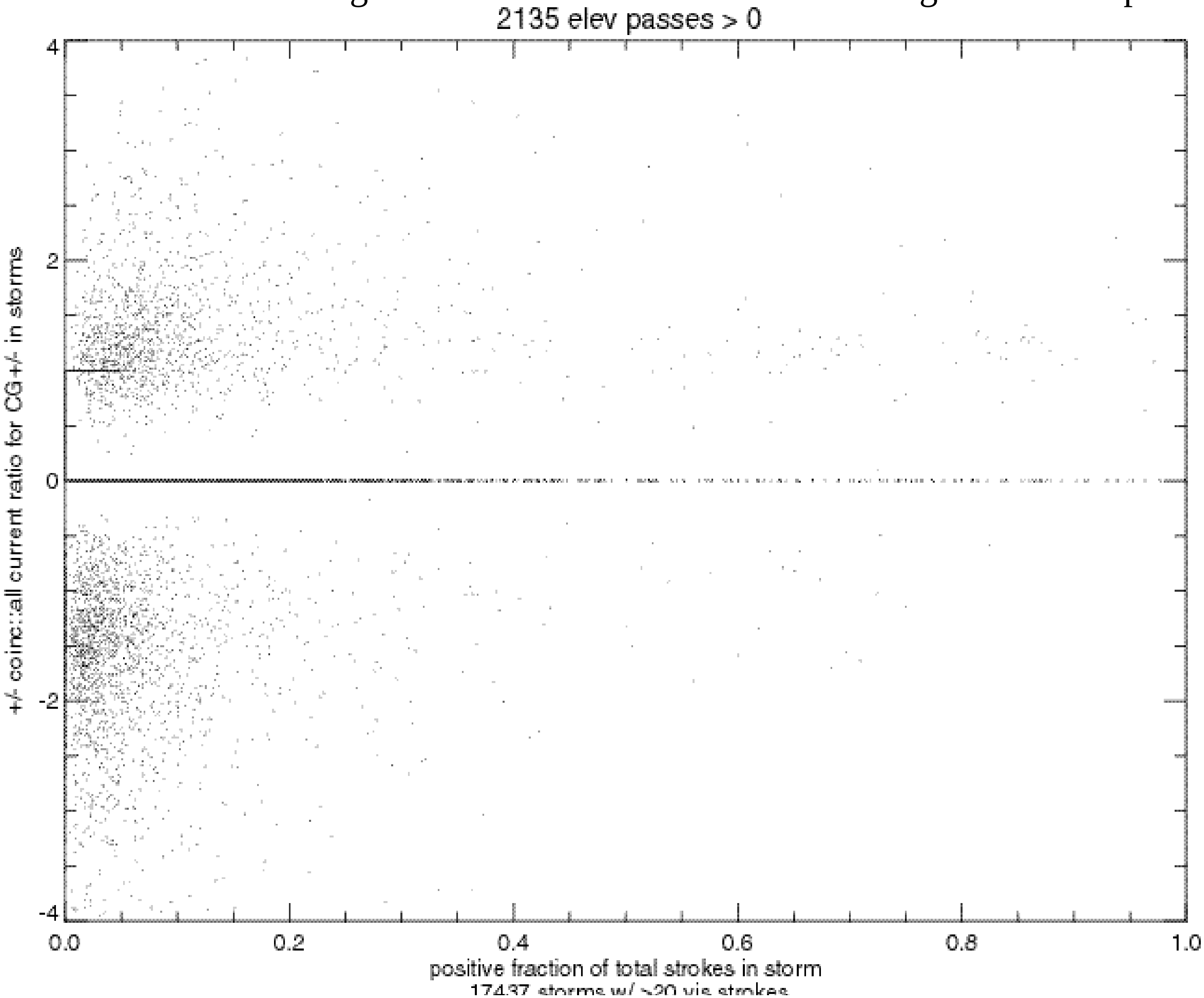
Similar to previous figure, but with the vertical current averaged over the subset of strokes which are coincident with FORTE VHF. (The stroke rate continues to pertain to all strokes in each “storm”.) Comparison of the two figures shows that the requirement of FORTE VHF coincidence dramatically skews the -CG strokes to higher currents, while the effect on +CG strokes is noticeable but less dramatic.



This figure graphs the fraction of NLDN strokes within a "storm" which are coincident with FORTE (vertical axis), vs the stroke rate within each storm, for all "storms" having >20 strokes visible to FORTE. The tendency for more efficient FORTE detection at low stroke rate is due to the correlation of low stroke rate with higher current (see previous two figures).



Ratio of “storm”-average vertical current for FORTE-coincident strokes to “storm-average vertical current for all strokes (vertical axis), vs fraction of total strokes in storm which are +CG. The basic result is that either -CG or +CG current amplitudes associated with FORTE coincidences tend to be higher than for the storm’s overall average current amplitude.



This plot shows most dramatically the correlation between *positive fraction* (the fraction of strokes in a storm which are positive CG) and the ratio of fraction of events which are FORTE-coincident. As the fraction of positive CGs increases, so does the fraction of strokes which are FORTE-coincident. The barchart is binned in units of 0.1 on the positive fraction variable.